PAIR-BREAKING QUANTUM SENSORS FOR RARE EVENT SEARCHES

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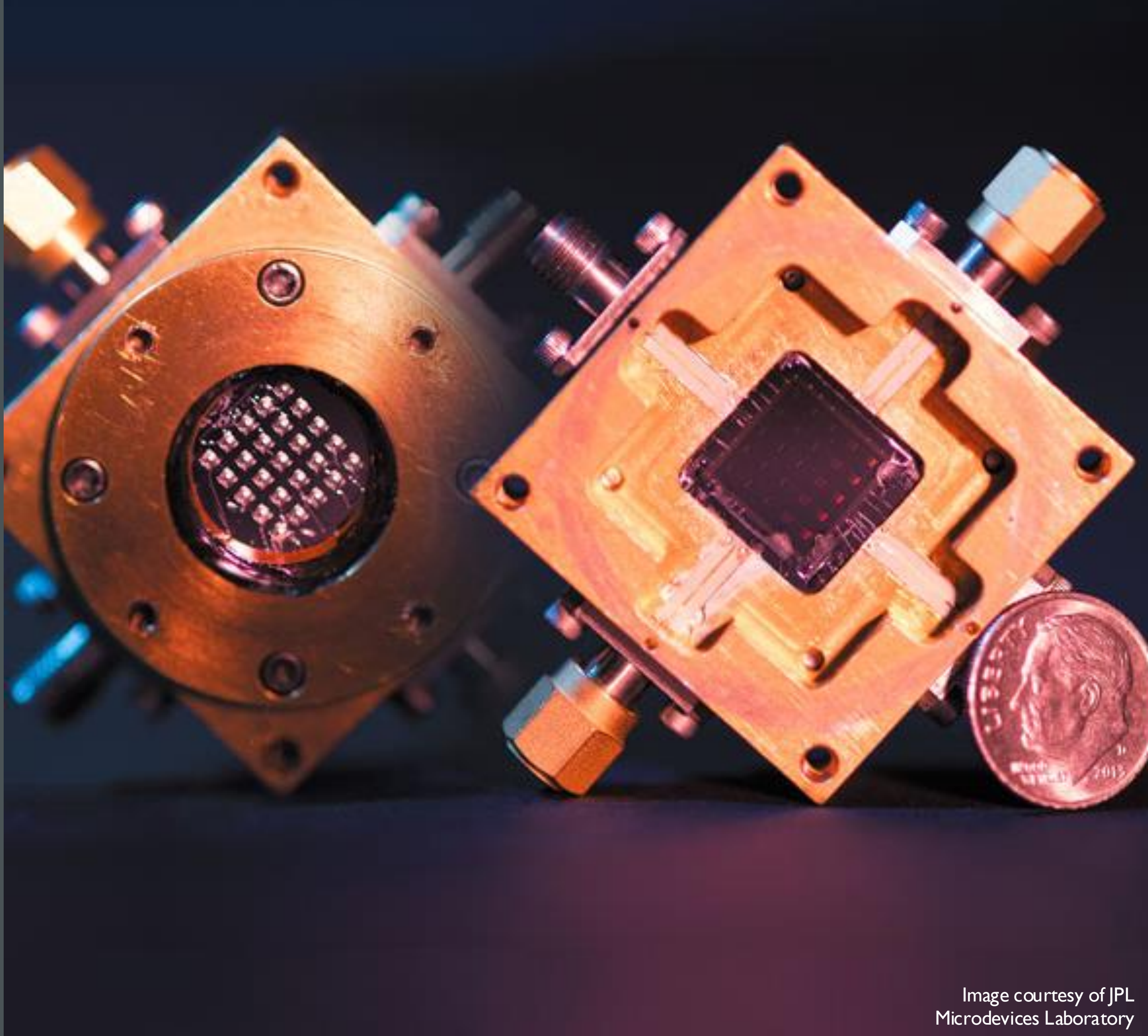

Image courtesy of JPL Microdevices Laboratory

Structure

1. Rare-event searches
    - The example of dark matter
2. Superconductors
    - Cooper-pairs & quasiparticles
    - Kinetic Inductance
    - Josephson Effect
3. Sensor Technologies (briefly)
    - SQUIDs
    - TESs
    - KIDs
    - SNSPDs
4. Quantum Sensors (QPDs, SQUATs)
    - A deeper look at JJs
    - What's a qubit?
    - "Parity" detection

Time permitting

5. Noise sources and evading noise

Rare-events: low probability, background limited, nuclear or particle physics phenomenon *that you can't (easily) engineer more of.*

e.g. you don't have a dark matter beam to turn up the intensity knob on. Need to be ready to sense whatever infrequent interaction you might have and reject everything else.

Axion Detection

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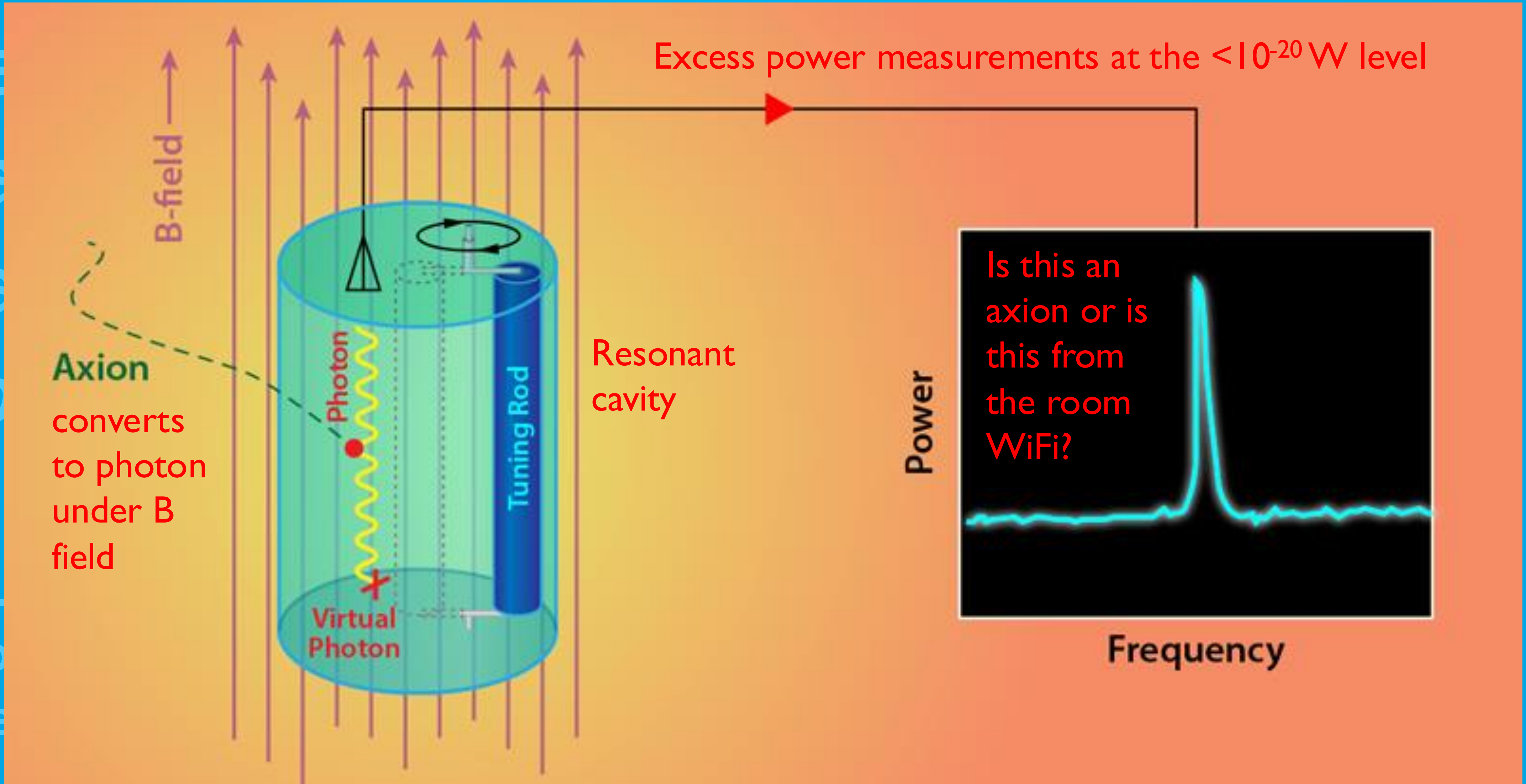
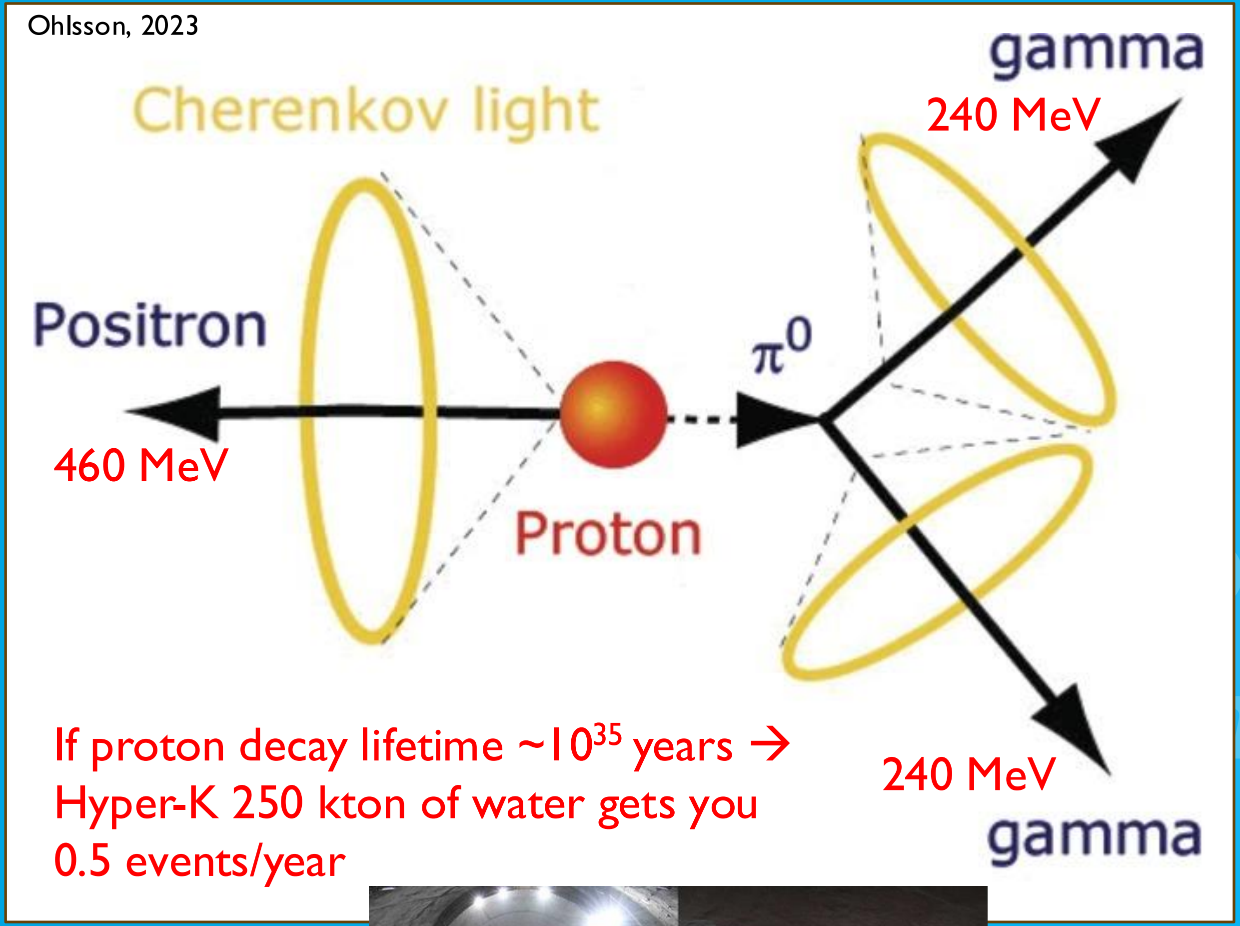
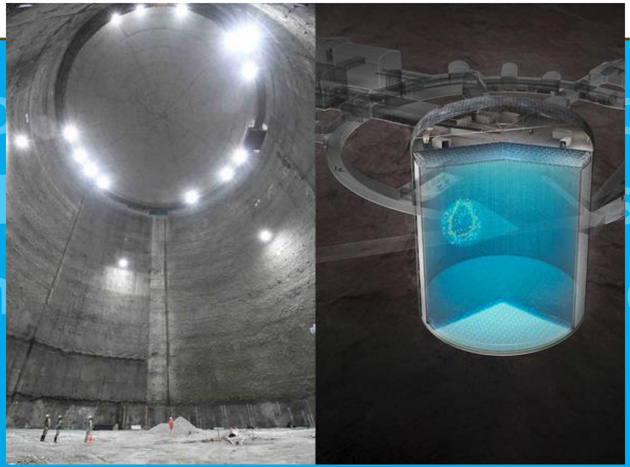
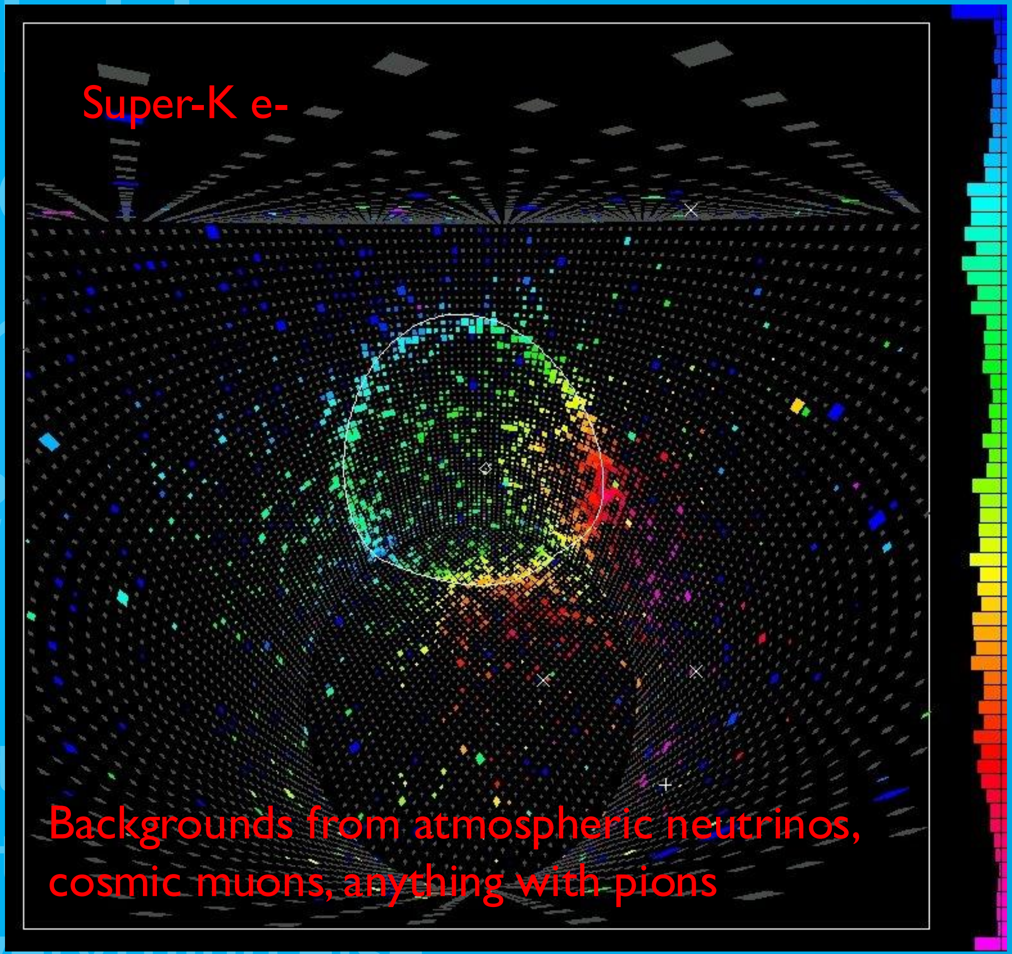


Boutan, Stonebaker 2019

Proton Decay

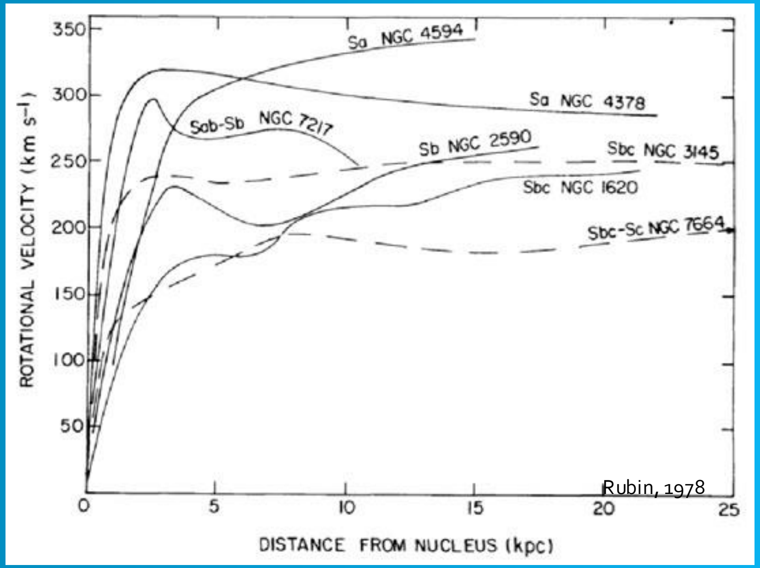


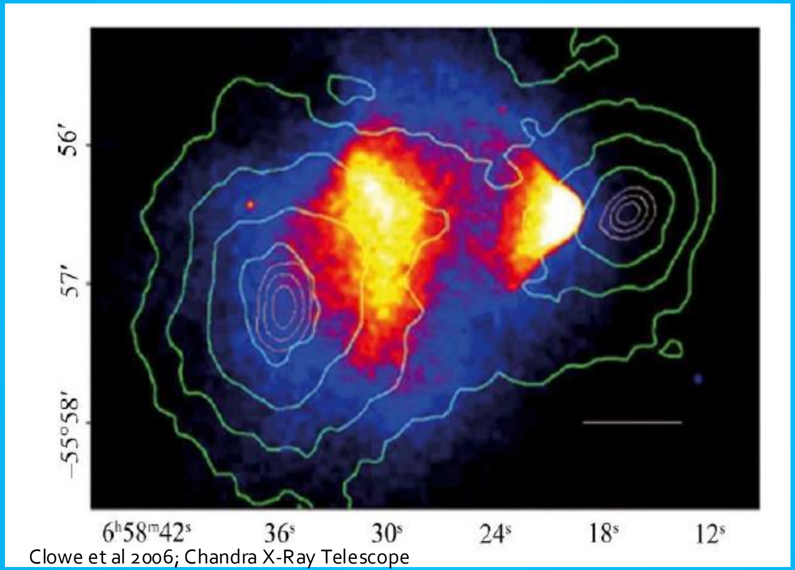


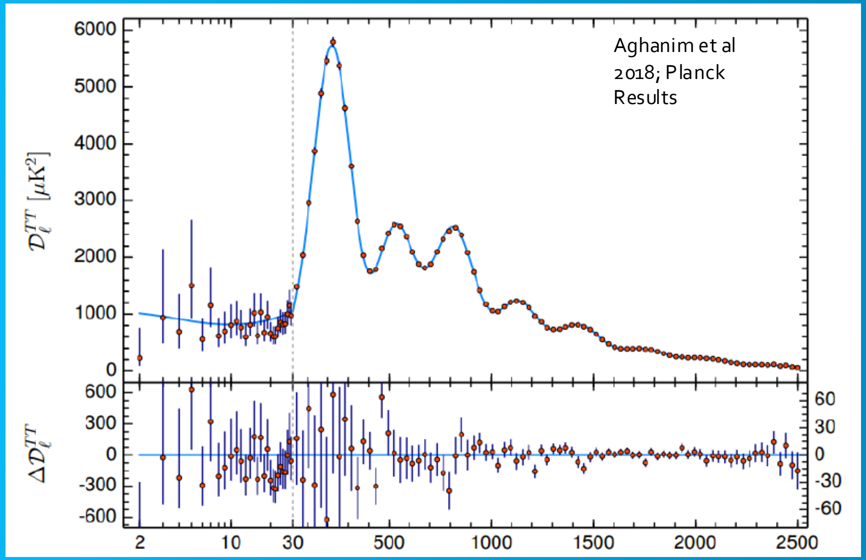


Dark Matter

Strong cosmological and astrophysical evidence for some missing matter in the universe comprising ~25% of the total mass-energy of the Universe.







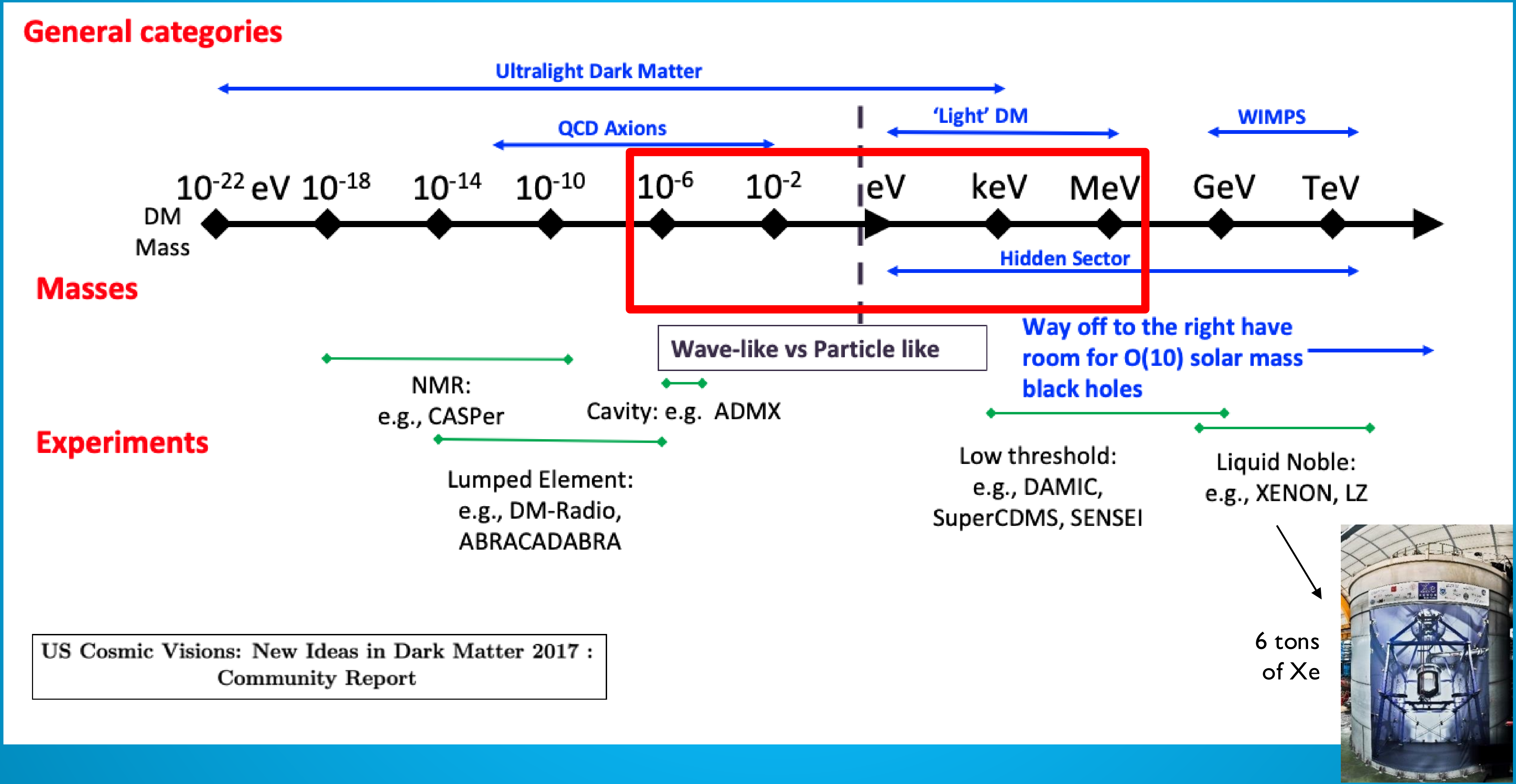
Rotational Velocity: Galaxy rotation curves showing flatness out to large radii, as opposed to expected decline

Bullet Cluster: the gravitational lens mass distribution of galaxy cluster collision varies from x-ray derived plasma distribution

CMB: Cosmological models of the early universe relic radiation require dark matter contribution

Upshot → ~5x more "Dark Matter" in Universe than regular baryonic matter

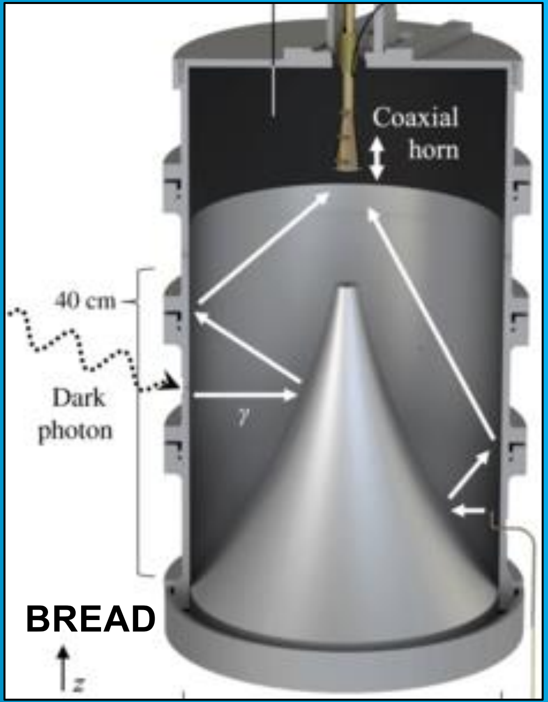
DM Parameter Space



Sensing DM

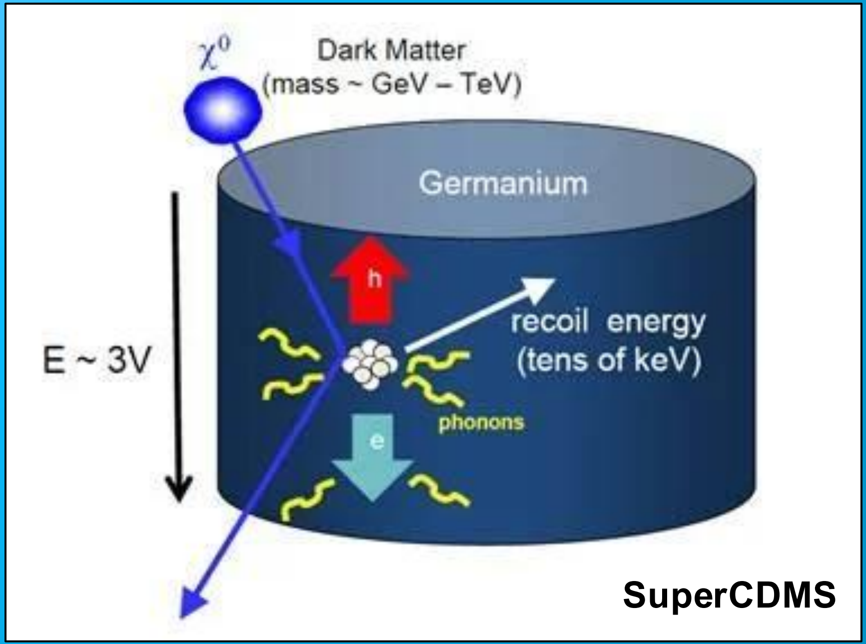
Wave-like

- e.g. Axions
- large occupation numbers
- may generate a single **photon**
- **How do you detect photons of few meV (THz)?**

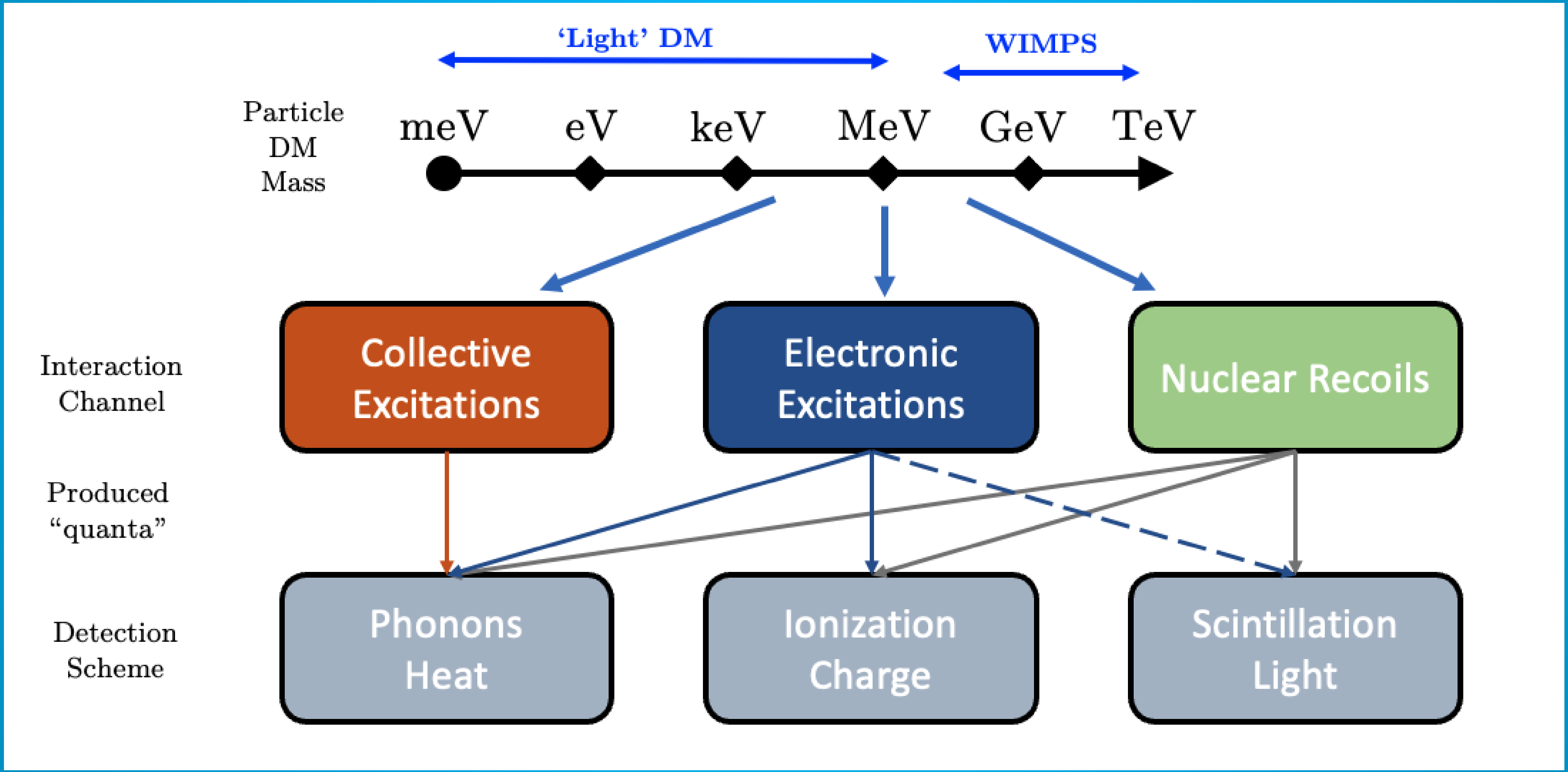


Particle-like

- e.g. LDM
- single particle scattering or absorption
- generate collective excitations like a **phonon**
- **How do you detect a 10 meV energy deposit?**



Interaction vs Detection Mechanism

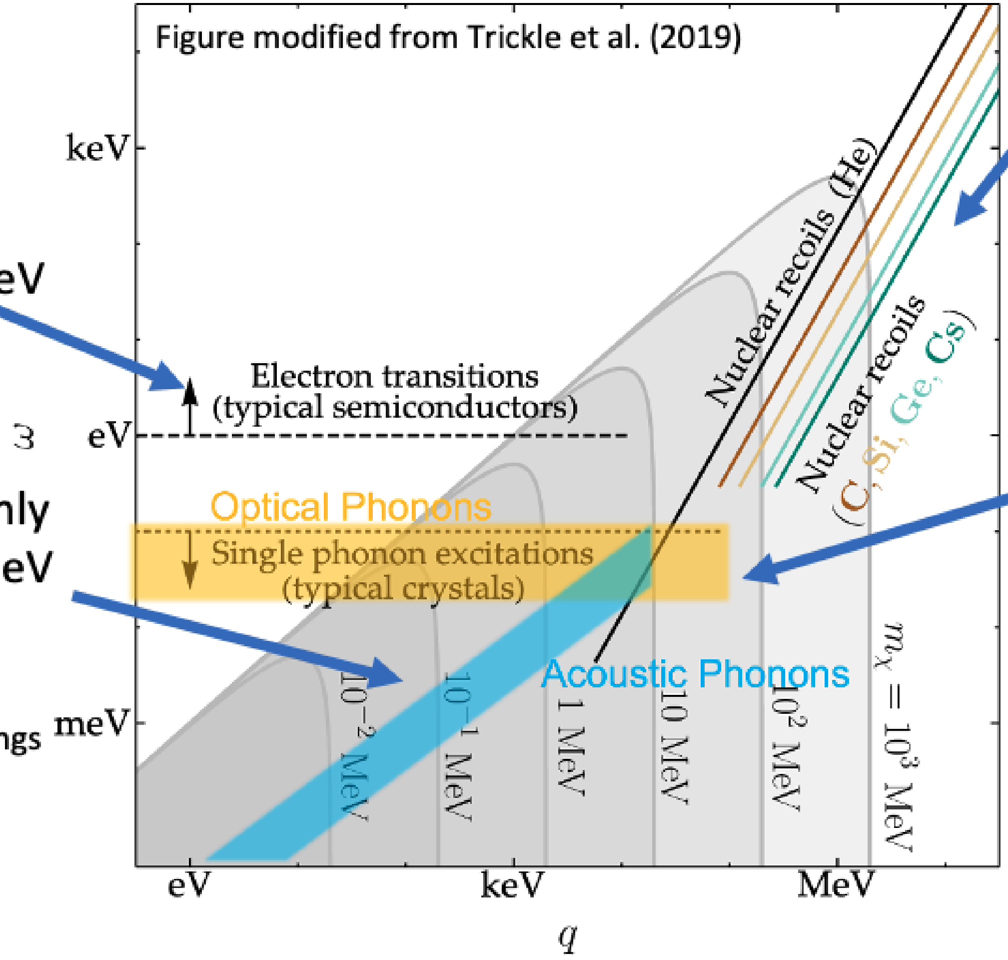


Kinematic space for particle like light DM

Electronic transitions ~eV scale

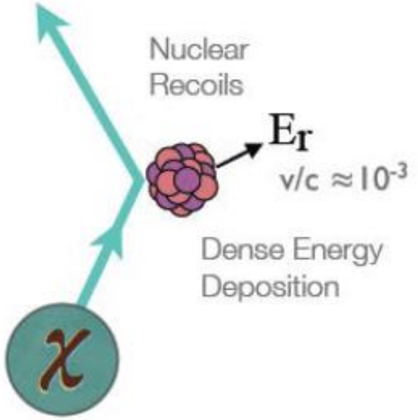
Phonons are basically only game in town for <10 MeV couplings*

*assuming no EM or other couplings



Nuclear recoil loci only goes down to where nuclei can be considered ~independent

Polar materials (e.g., GaAs, AlO3) can have strong optical phonon excitations for certain DM candidates with EM couplings



The Low-Threshold Challenge

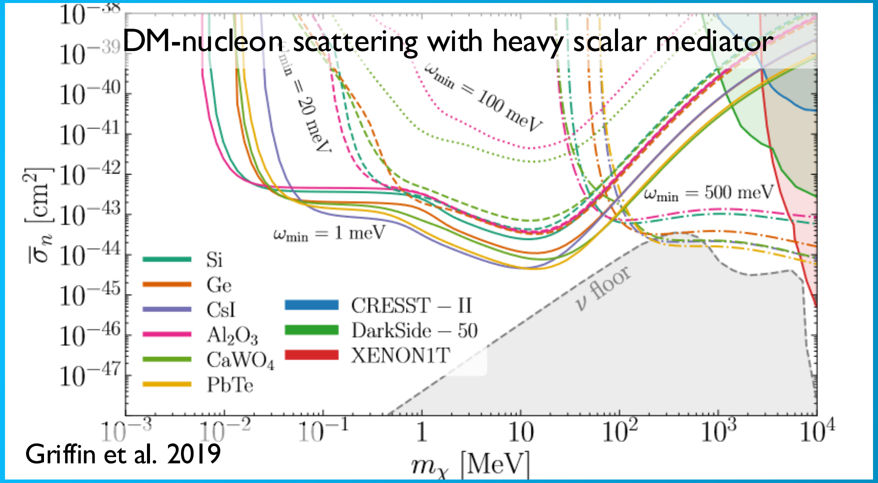
- Iterating on existing detector technologies?
- Challenges:
  - Moving down the mass scale, energy deposits get much smaller

$$\Delta E \lesssim 70\ \mathrm{eV}\left(\frac{m_\chi}{500\ \mathrm{MeV}}\right)^2\left(\frac{m_T}{28\ \mathrm{GeV}}\right)^{-1}\quad (m_\chi << m_T)$$
$$\lesssim 4\ \mathrm{eV}\left(\frac{m_T}{511\ \mathrm{keV}}\right)\quad (m_\chi >> m_T)$$

  - Do not produce enough *quanta* to work in semi-classical continuous picture. Must think about individual excitations*

Question:
1. What tools exist to measure energy deposits at O(ueV) to O(meV)?
2. Can we leverage techniques from our CM, AMO, Materials etc. colleagues?

Interaction rates for these light mass DM can be close to O(Hz)/kg!



Griffin et al. 2019

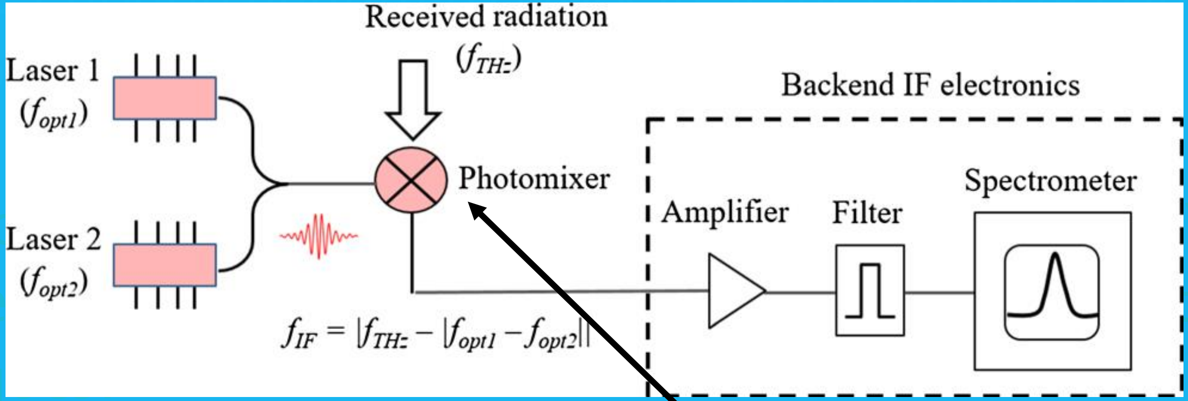
* Just because you can count things doesn't necessarily make it "quantum", a PMT is a quanta device.

GHz-THz Photon Sensor Gap

"…characterized by a "THz gap" due to the difficulty in researching and manufacturing high-performance THz sources … and detectors using traditional methods."

-- Chen, 2024, APR

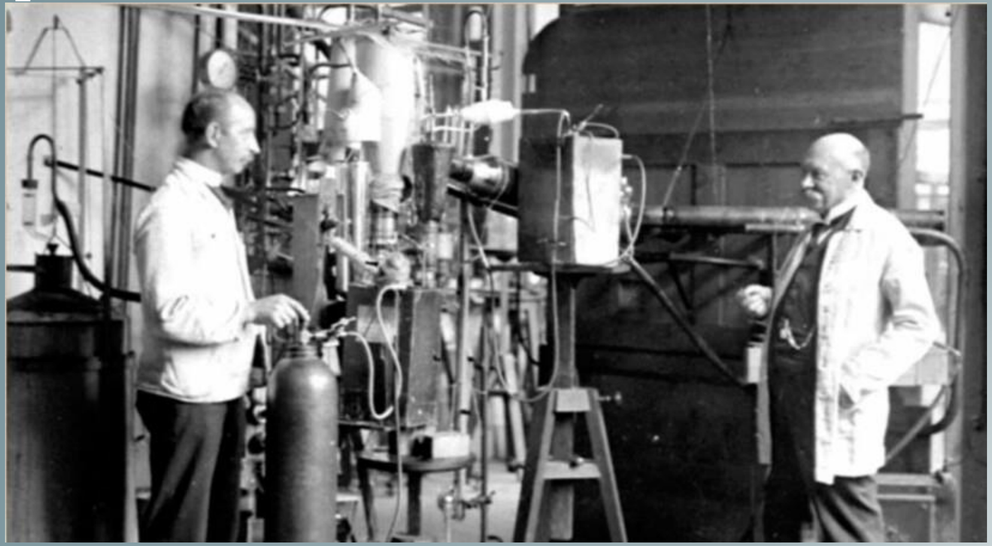
e.g. current state of art: mix received radiation with a reference signal and readout in an RF band

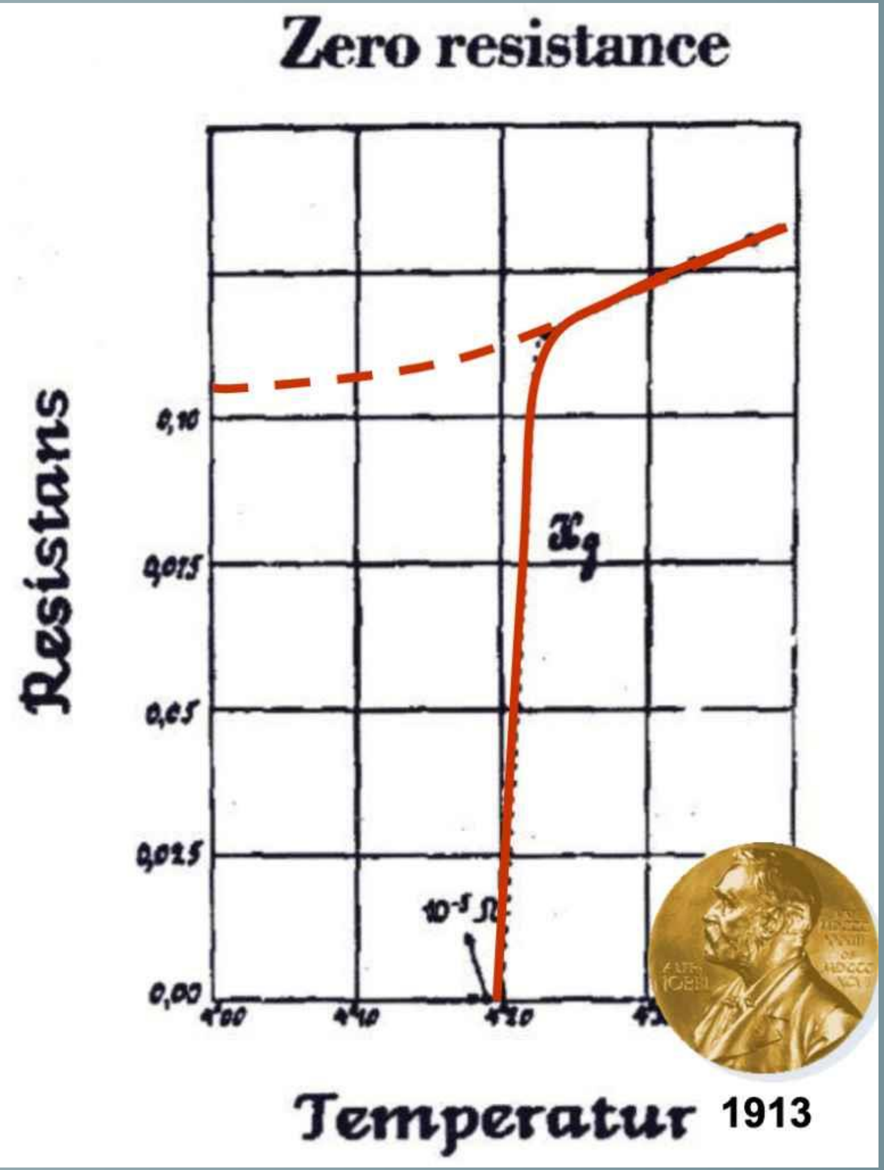


Mixer can be SIS junction, Schottky Diode, HEB etc. with some non-linearity

A (very) brief foray into superconductivity

Superconductors





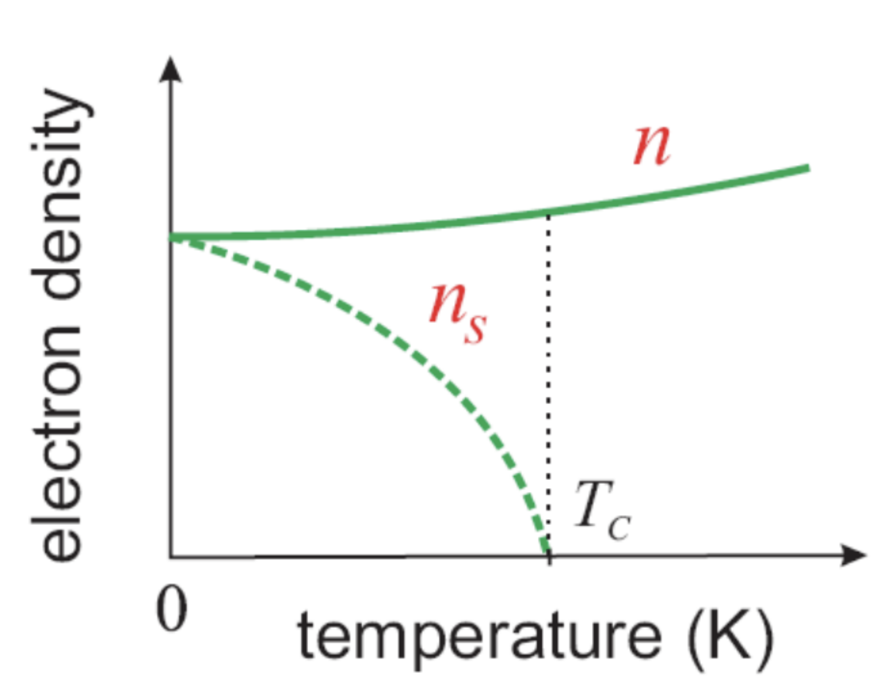
- Discovered by Kamerlingh Onnes in 1911 during attempts to liquefy helium.
- Measuring resistivity of Hg wires, noticed that the electrical resistance dropped to ~0 at 4.2K (transition temperature T_c)
- By 1912, showed that the resistive state is restored in a magnetic field (critical field H_c) or at high transport currents (critical current density J_c)

London Theory

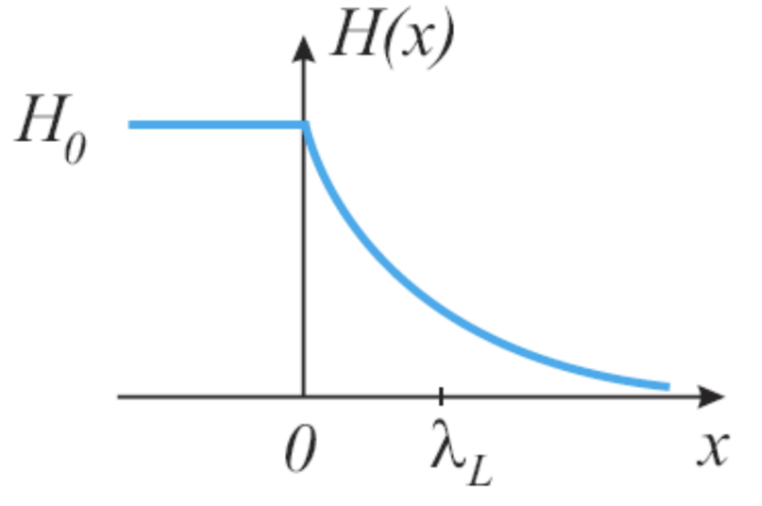
Fritz and Heinz London

Phenomenological model, 1935: how a fluid of super-electrons* responds to EM fields -> dissipationless motion and opposes B fields

Predicts a screening length for magnetic fields – London penetration depth



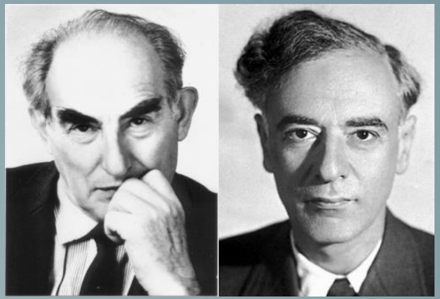
$$\lambda = \left(\frac{mc^2}{4\pi n_s e^2} \right)^{1/2}$$



Element	Al	Nb (crystal)	Nb (film)	Pb	Sn	YBCO
λ(0), Å	500	470	900	390	510	1700

*in a two-fluid model; later known as Cooper-pairs

Ginzburg-Landau Theory



Vitaly Ginzburg, Lev Landau

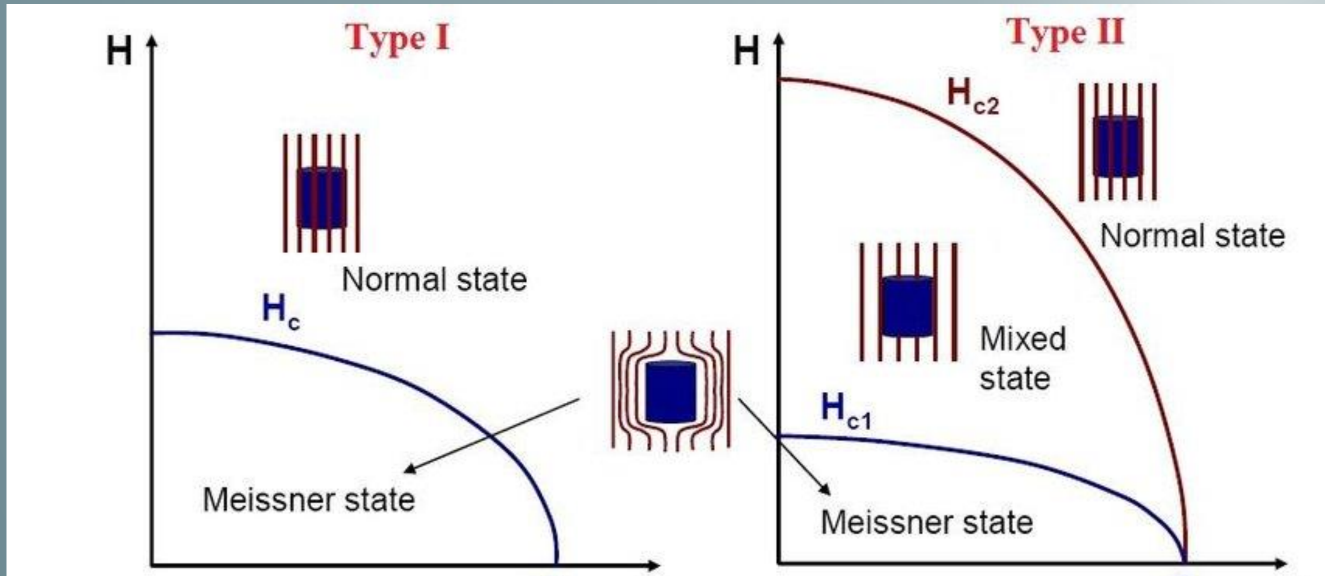
Macroscopic theory, 1950: applied ideas of statistical mechanics – treated the superconducting transition as a phase transition. Introduced a complex order parameter, and minimizes free energy

$$|\psi|^2 \propto n_s$$

Further permits a coherence length which describes size of spatial variations in super-electron density

Metal	coherence length ξ_0, in 10^{-6} cm
Sn	23.
Al	160.
Pb	8.3
Cd	76.
Nb	3.8

Meservey, Schwartz

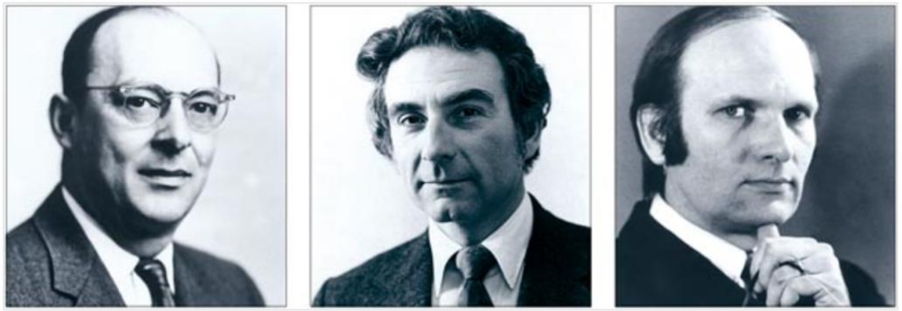


Cayado, 2012

In combination with penetration depth, can distinguish between Type I and II superconductors and response to B fields.

BCS Theory

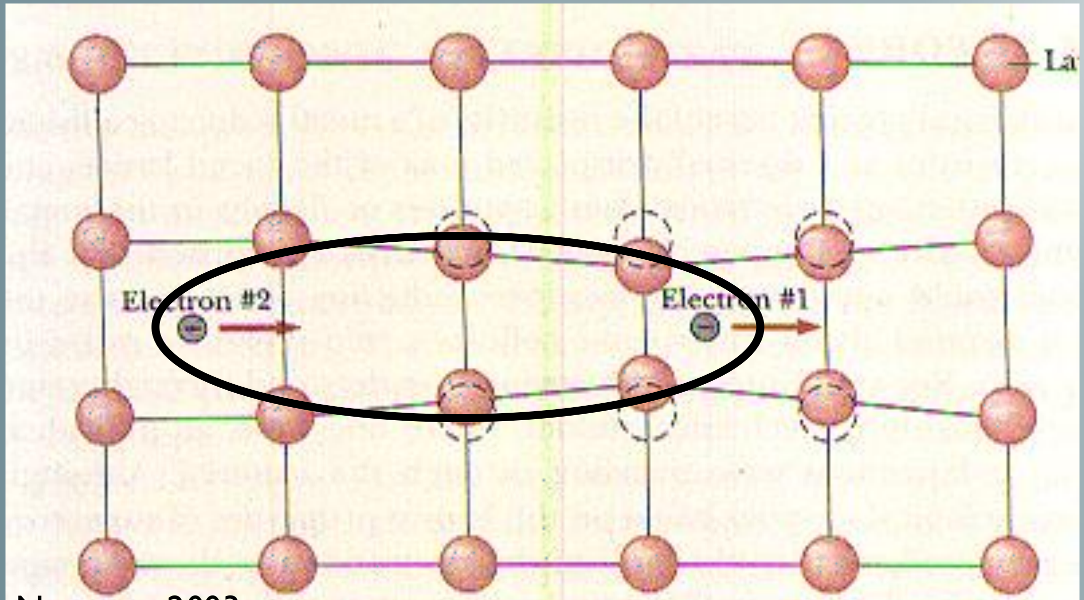
Microscopic theory, 1957: electrons form bound pairs, Cooper pairs, that condense into a quantum state allowing resistance-free current. Pairing mediated by lattice phonons*



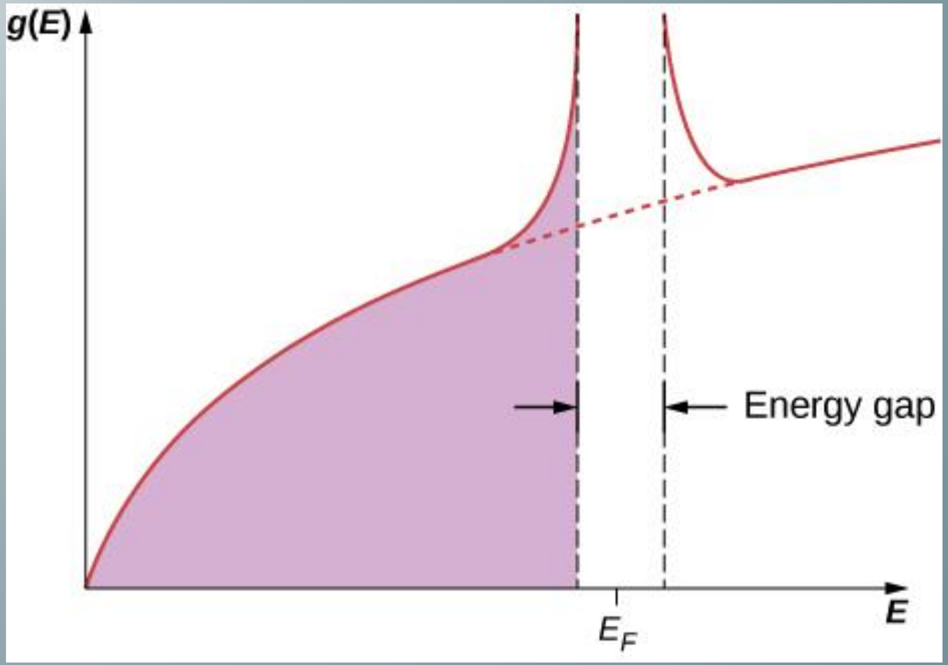
John Bardeen, Leon Cooper, John Schrieffer

Gap energy Δ for pairing of electrons.

$$2\Delta = 3.52 k_B T_c$$



Newman, 2003



*at least in some LTS systems; HTS are less understood

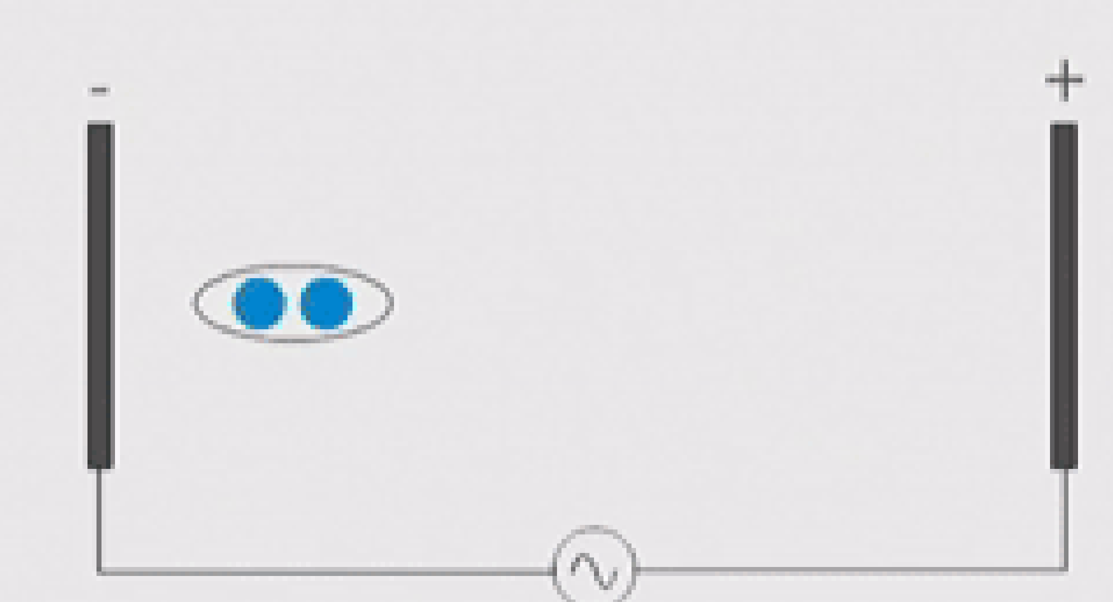
Kinetic Inductance

Inductance arising from inertia of Cooper pairs as they respond to an external field → stored energy in the kinetic movement rather than a magnetic field

In a superconductor:

$$L_{sc} = L_{geo} + L_K$$

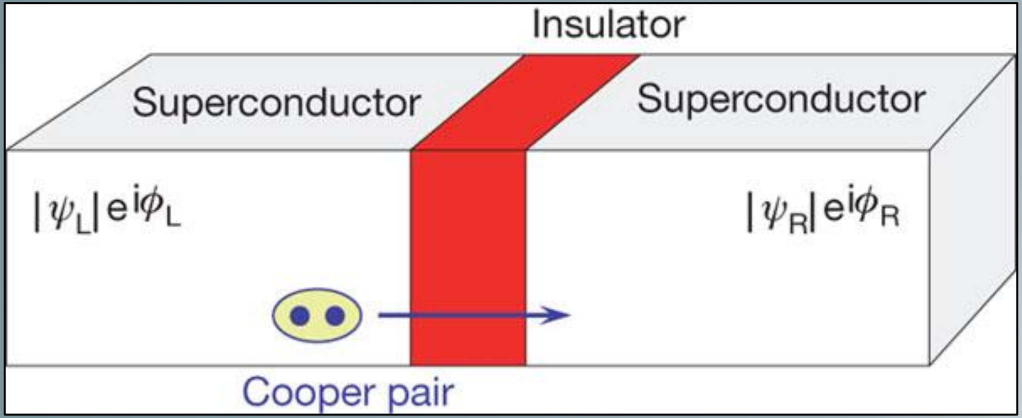
$$L_K = \left(\frac{m_e}{2n_c e^2}\right)\left(\frac{l}{A}\right)$$

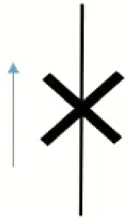


Mazin, 2015

Note how the kinetic inductance is related to the Cooper pair density n_c → changes to this density can manifest as observable changes to electrical properties of any superconducting circuit…

Josephson Junctions I





$\phi = \delta_2 - \delta_1$

$I = I_C \sin\phi$

$V = \phi_0 \frac{d\phi}{dt}$

$\frac{dI}{dt} = \underbrace{\frac{I_c}{\phi_0}}_{1/L} V$ at small I.

Slap together two superconductors separated by a thin barrier, Cooper pairs can begin to tunnel quantum mechanically → Described by macroscopic wave functions with phase difference.

Leads to interesting effects:

DC Josephson effect: current can flow with zero voltage
AC Josephson effect: voltage can cause time evolution of phase and an oscillating current
Non-linear inductance: energy stored in the phase "stiffness" across the junction

Upshot: control coherent macroscopic quantum states.

Why do we care?

Energy to break Cooper pair: 2Δ

$$2\Delta(T) = 3.2 k_B T_c \sqrt{1 - \frac{T}{T_c}}$$

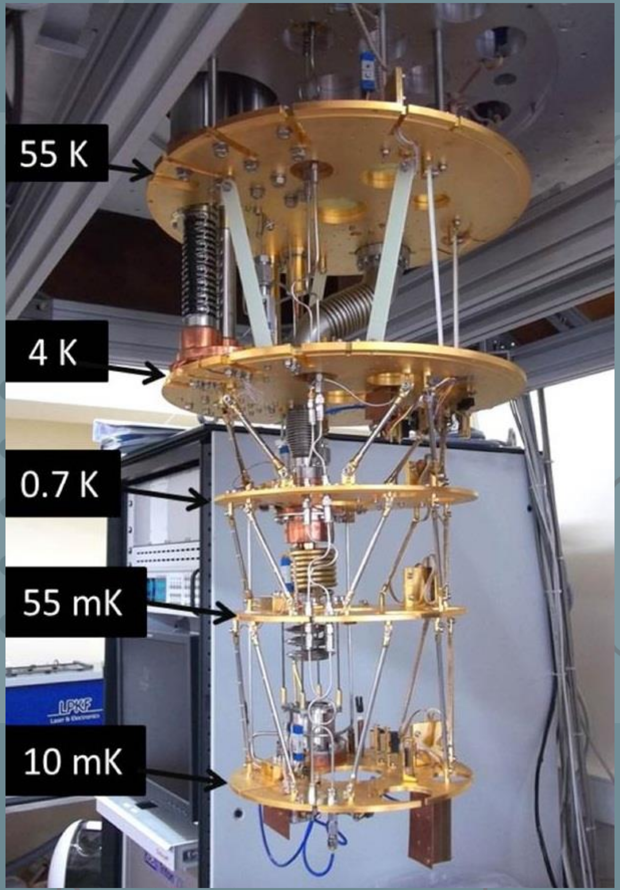
Nb	T_c = 9.3 K	2Δ = 2.6 meV
TiNx	T_c = 5.6 K	2Δ = 1.5 meV
Al	T_c = 1.2 K	2Δ = 330 μeV
Hf	T_c = 165 mK	2Δ = 44 μeV
AlMn	T_c ≈ 100 mK	2Δ ≈ 26 μeV

@ 10 mK

+ Gaps down to ueV scale (semiconductor band gaps ~ 1 eV)
+ Zero resistance means no intrinsic DC dissipation. Can build circuits limited by *quantum noise*
+ Can exploit phase transition physics and sharp changes with temperature/magnetic field/current
+ Access to macroscopic quantum states

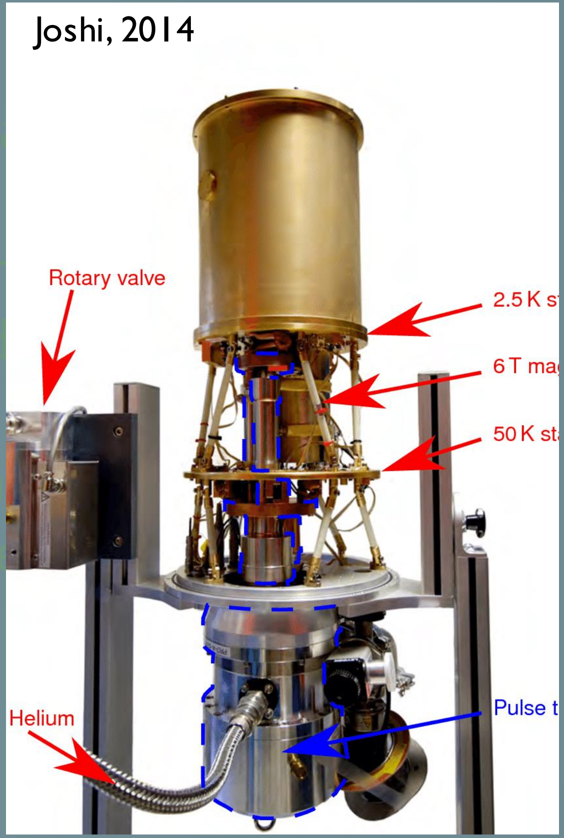
- Requires cryogenic temperatures (mK)
- Complex wiring and readout schemes might limit scalability
- New, interesting, and frightening sources of noise (Two-Level Systems)
- Susceptible to every background known to man (B fields, radiation, vibrations, photons)

Cryogenics



Dilution refrigeration: uses thermodynamics of mixing He3/He4 to get down to mK temperatures

He3 fridge: evaporative cooling from pumping on He3 in a vacuum



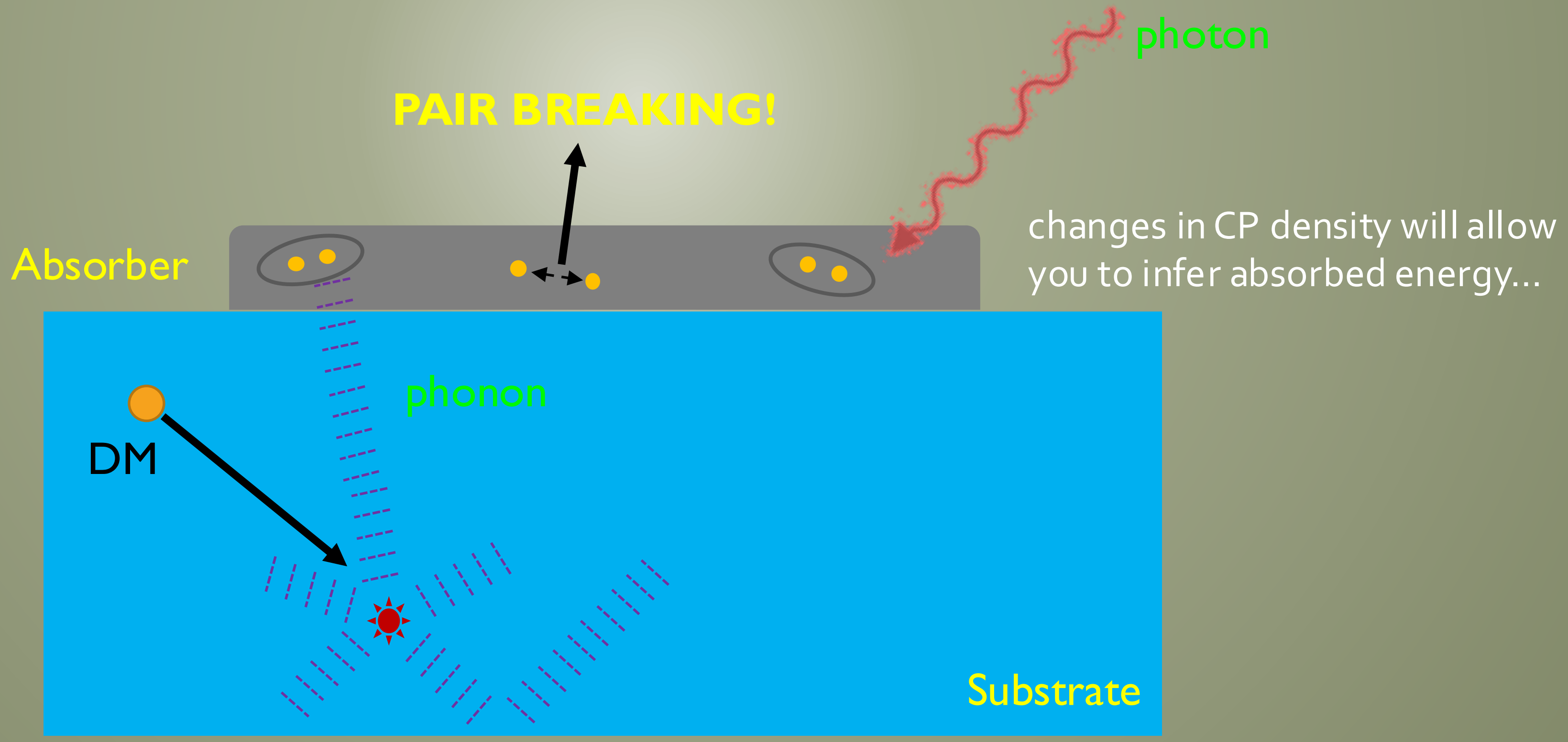
Adiabatic diamagnetization refrigerator (ADR): magnetize/demagnetize a paramagnetic salt

Sensor Architecture

Relevant features to exploit:

- Sharp phase transition → large responsivity
- Collective pairing energy is small → ueV to meV binding energies
  - Inductance due to Cooper pair inertia → Kinetic Inductance
  - Phase-coherent tunneling across a weak link → macroscopic state change

Sensor modalities:



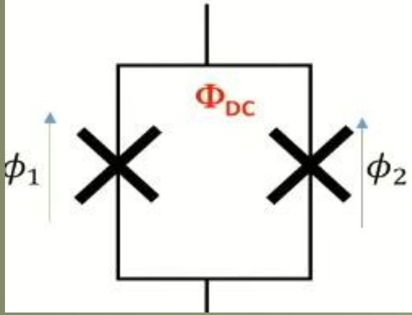
Sensor technologies

★ If I work on it

SQUIDs

Stick two Josephson junctions in a loop structure. Magnetic flux that threads the loop shifts the accumulated phase and modulates the current → like two paths in an interferometer

Extremely sensitive magnetometer

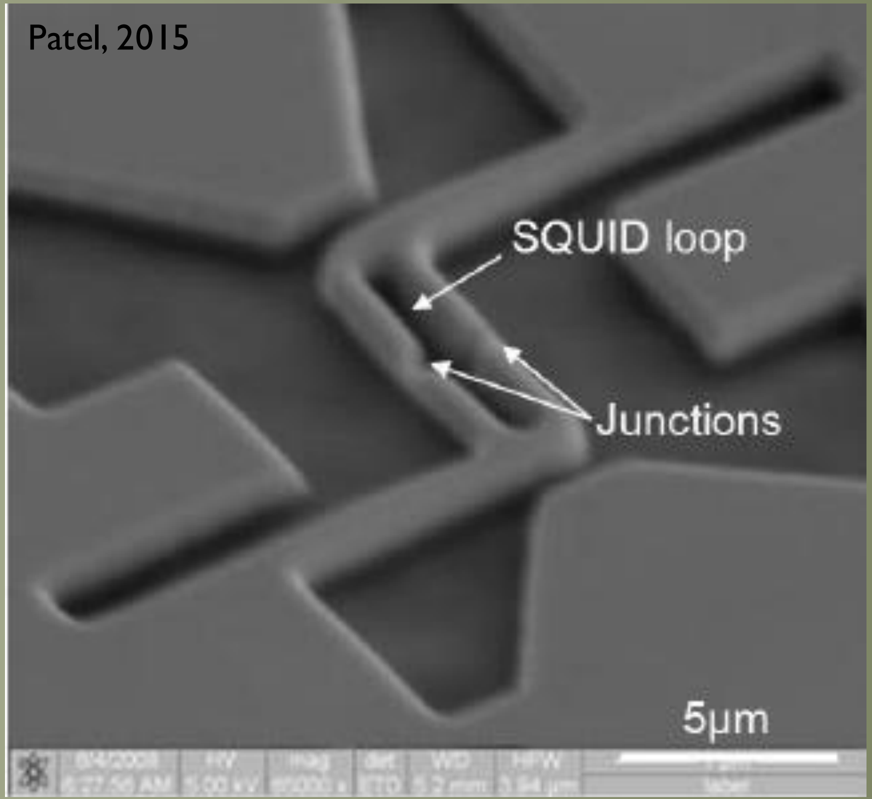


$$\phi_1 - \phi_2 = \phi_{DC}$$

$$I = I_C\,(\sin\phi_1 + \sin\phi_2) = 2I_c\cos\left(\frac{\phi_1 - \phi_2}{2}\right)\sin\left(\frac{\phi_1 + \phi_2}{2}\right)$$

$$I = I_c\cos\Phi_{DC}\,\sin\phi$$

Patel, 2015

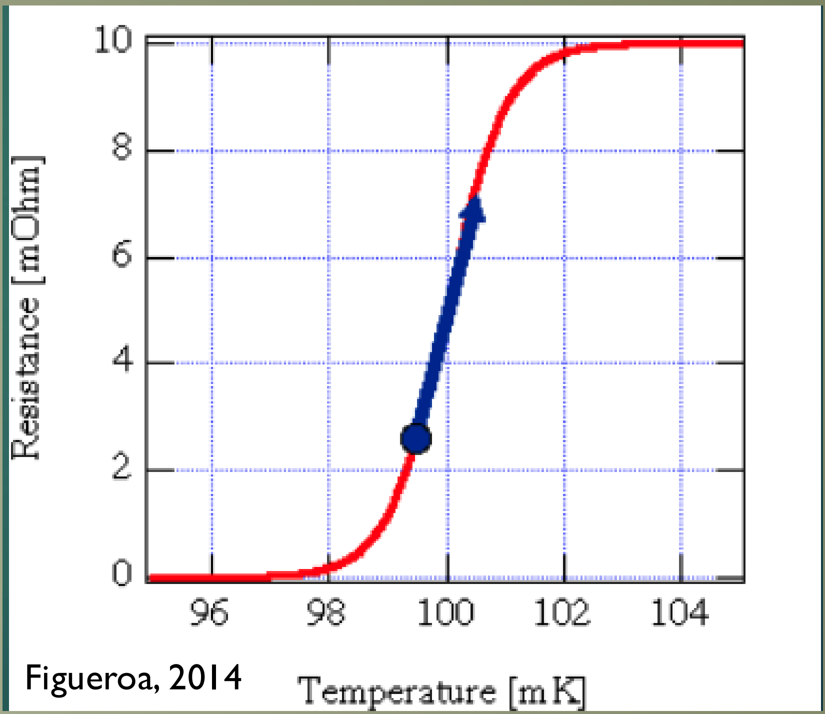


$$\frac{dI}{dt} = \underbrace{\frac{I_c\cos\Phi_{DC}}{\phi_0}}_{1/L} V$$

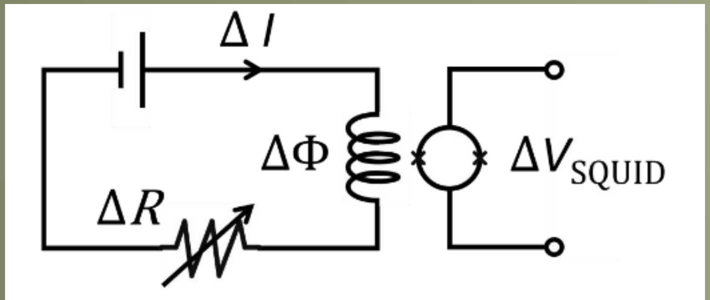
Also, flux tunable inductance can be used for other purposes: amplification, readout

Transition Edge Sensors (TESs)

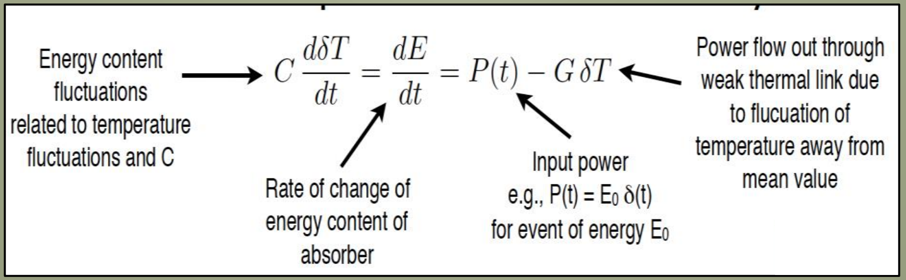
- Bias a superconducting sample to sit at transition temperature
- Couple this sample to a larger bath, provides cooling and measure resistance/temperature/power change
- Can operate in electrothermal feedback, and use e.g. SQUIDs for stable operation and readout

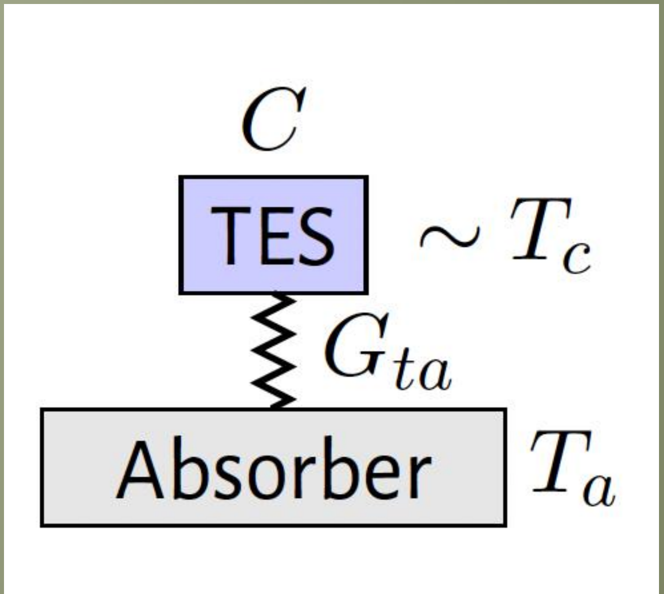


Figueroa, 2014



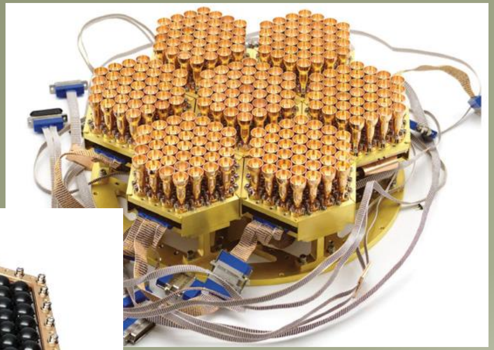
Temperature rise set by power balance



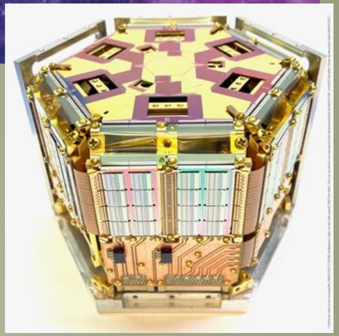


TESs for photons

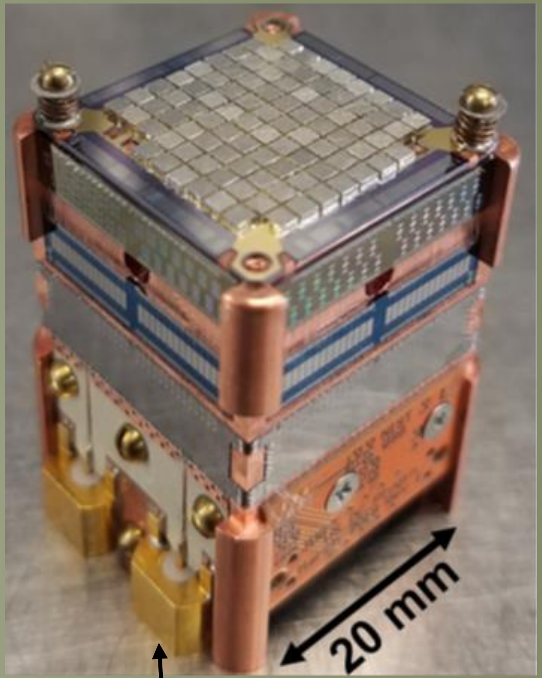
Have been used for everything!



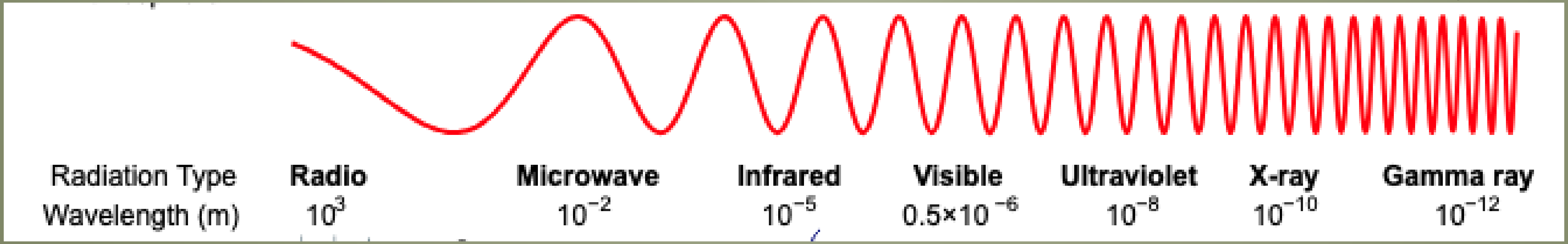
CMB Experiments in 40-300 GHz range BICEP, SPT, CLASS, POLARBEAR….



Upcoming Athena X-Ray space mission



NIST Gamma array “snout” with Sn absorbers



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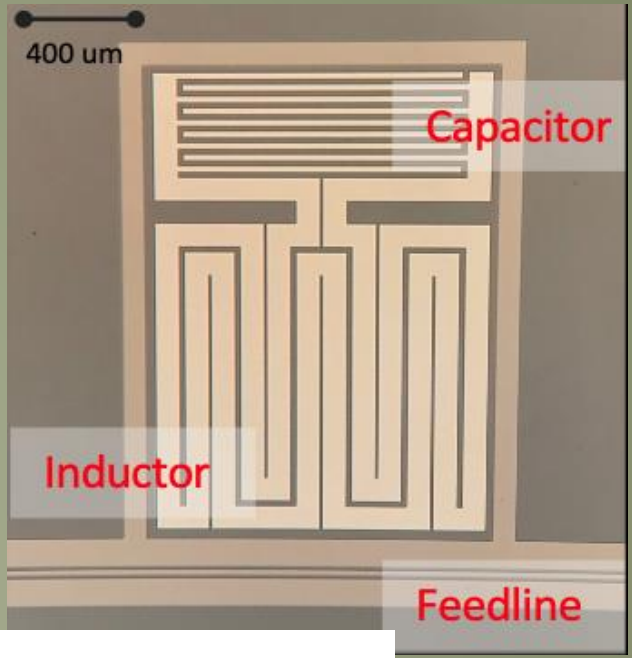
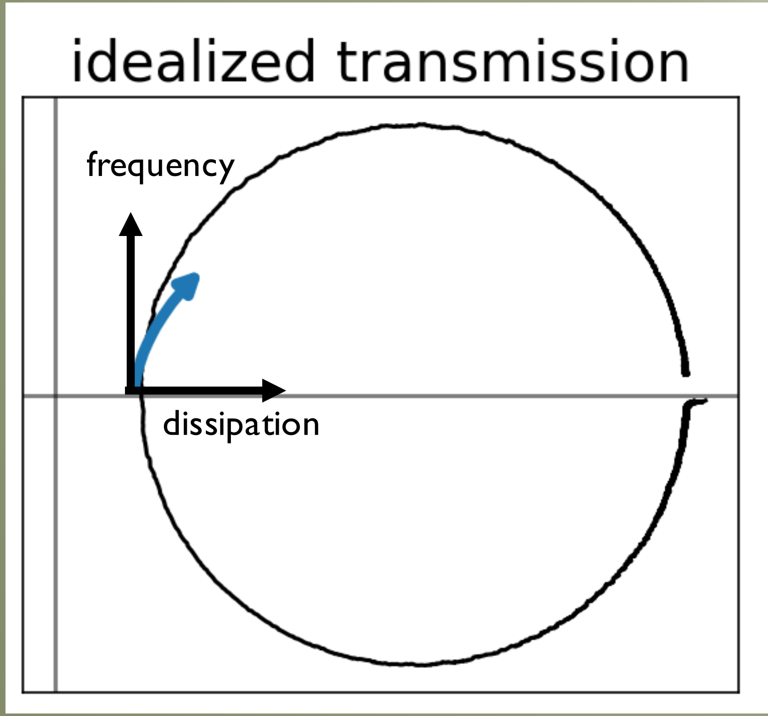
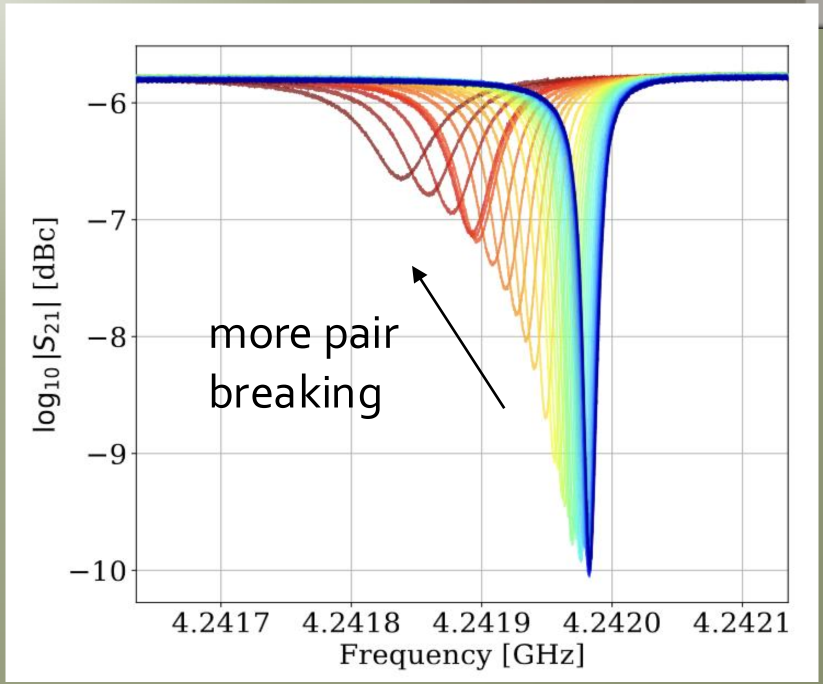
Kinetic Inductance Detectors

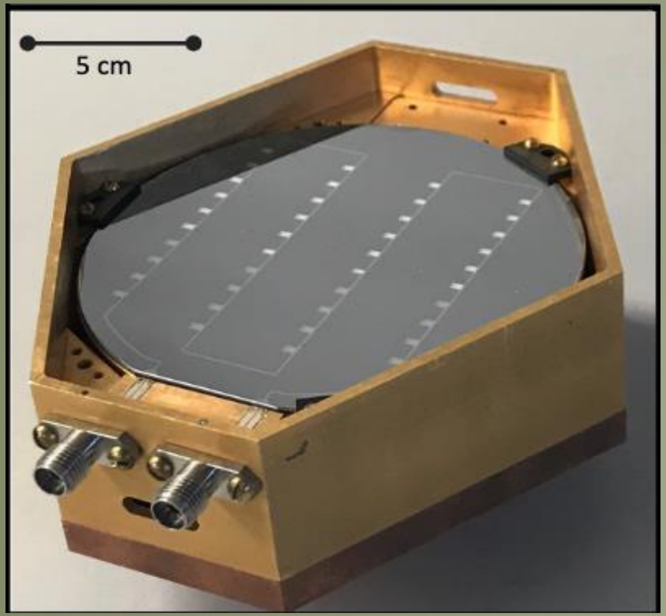


- Pattern superconductor into an LC resonator
- Total inductance = geometric inductance + kinetic inductance
- Measure transmission across resonator → how is the CP density changing
- Very high resonator Qs (10^6) achievable, so thousands of O(GHz) resonators can be chained on a single feedline with O(kHz) linewidths → simple cryogenic multiplexing

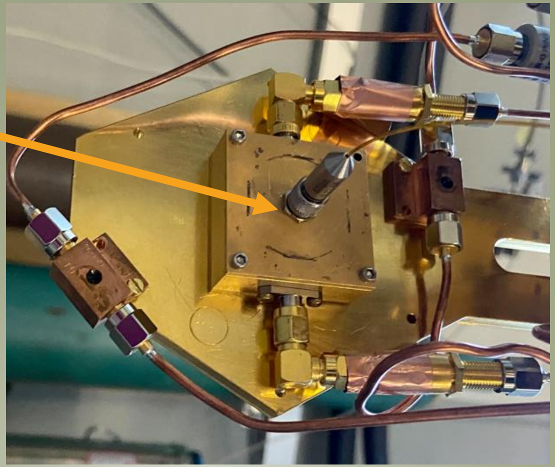




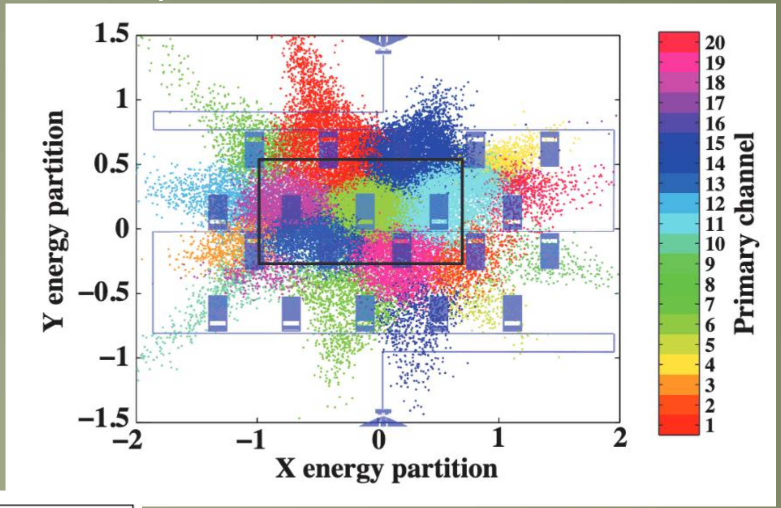
★ Kinetic Inductance Phonon Mediated Detectors

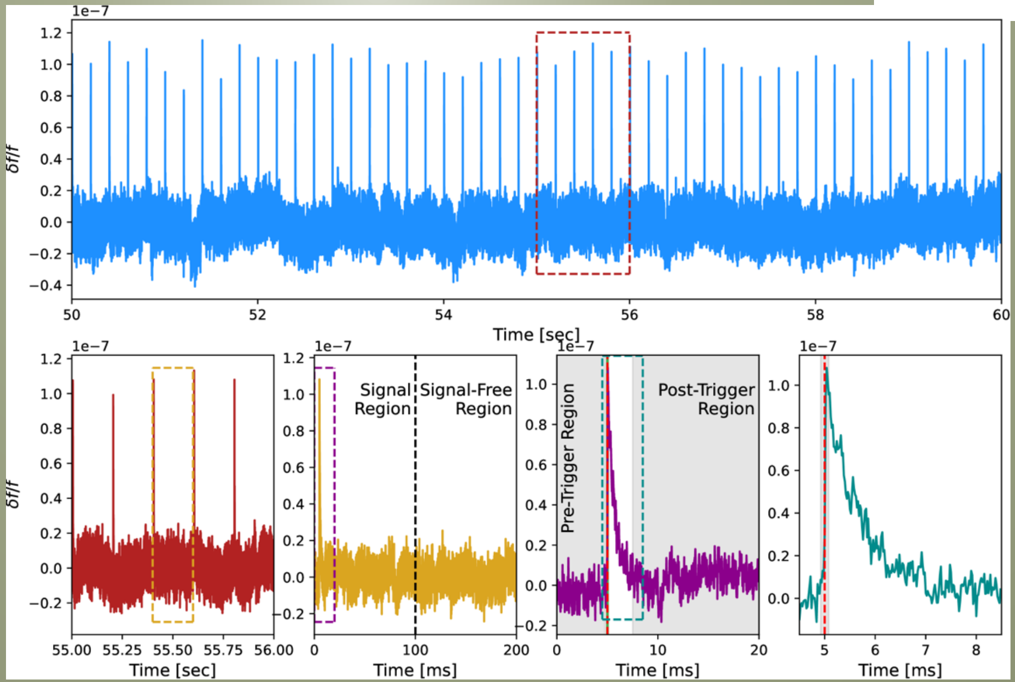


Optical Fiber



Exposure to a radioactive source





	small device @ FNAL	prototype device
η_{ph}	0.8%	7%
$\sigma_{E,abs}$	2.5eV	6eV
τ_{pulse}	~3ms	50us

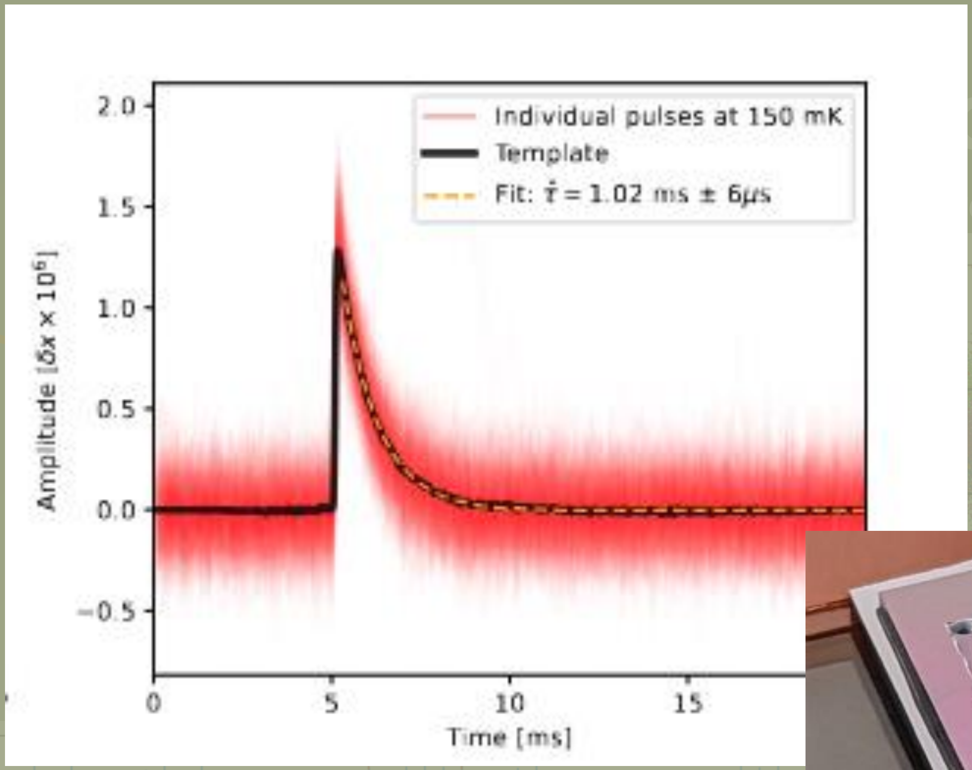
Fermilab

SLAC

LED testing → using expected shot noise behavior to perform absolute calibration.

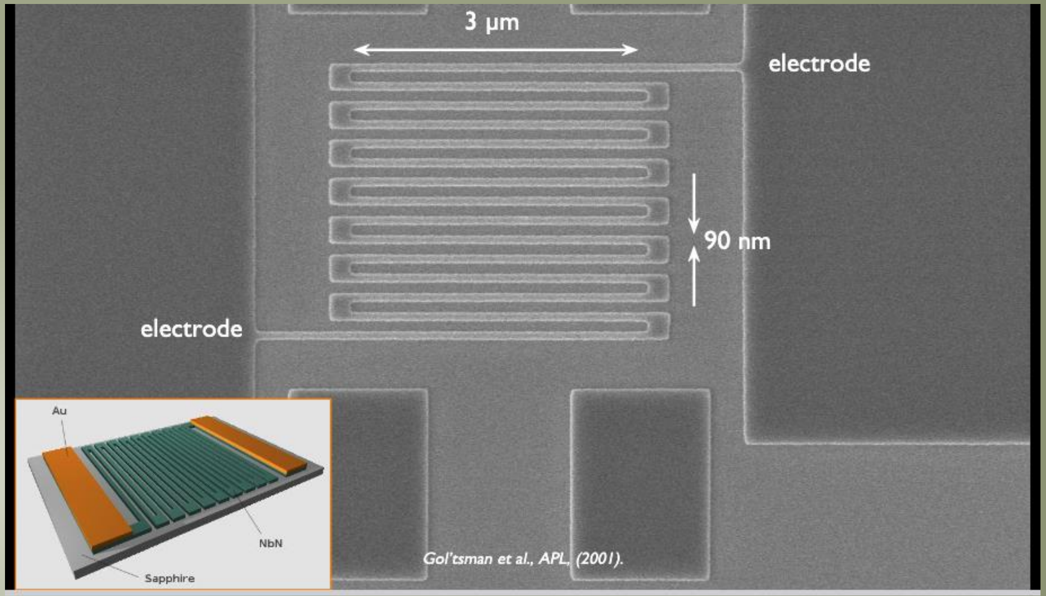
https://doi.org/10.1103/PhysRevApplied.22.044045

Go to Rito Thakur's talk on Thurs to learn about counting 12 THz photons with a KID

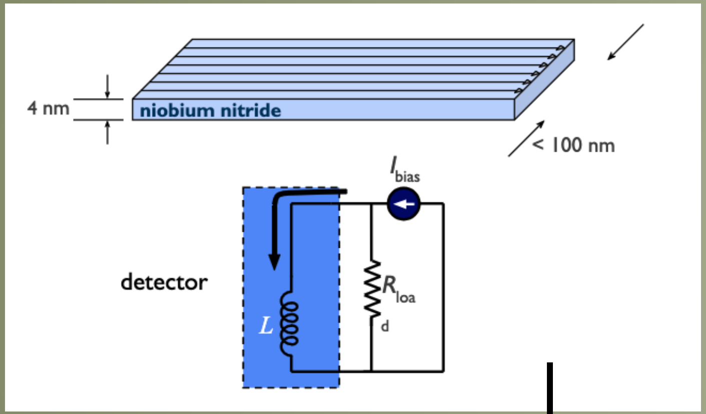


Superconducting Nanowire Single Photon Detectors (SNSPDs)

Take a thin meander of superconducting wire and bias it near its transition point.

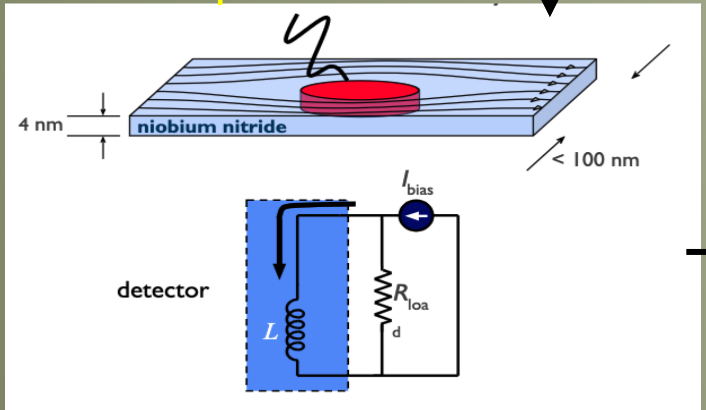


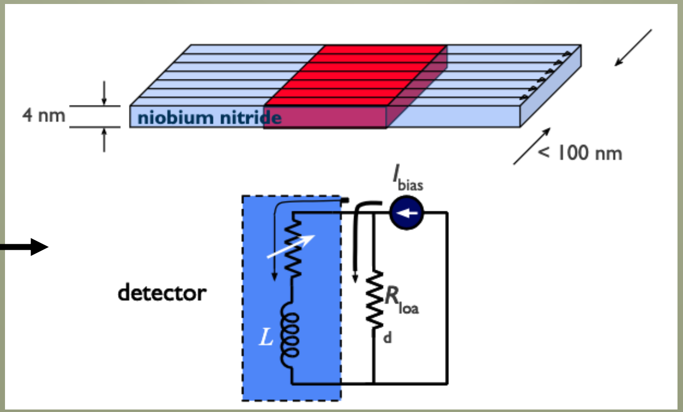
800x500 pixel camera, NIST 2023



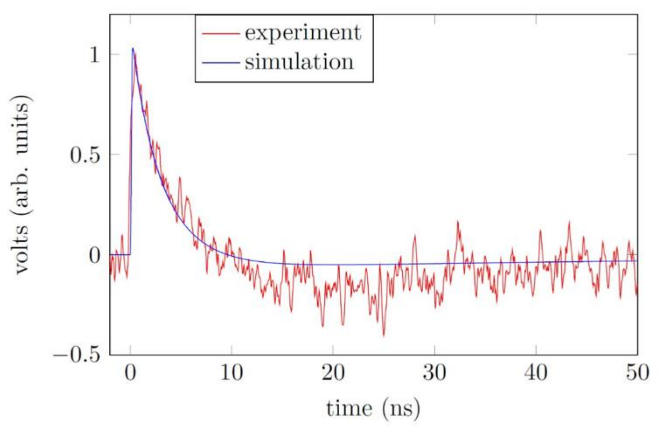
Cools back down

Absorbs a photon





Forms a hotspot and diverts current

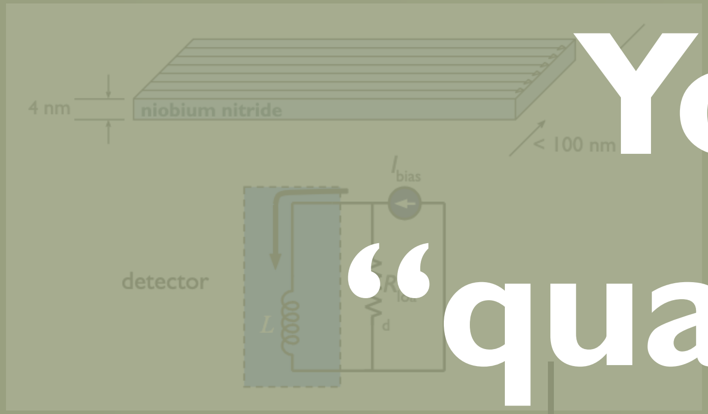


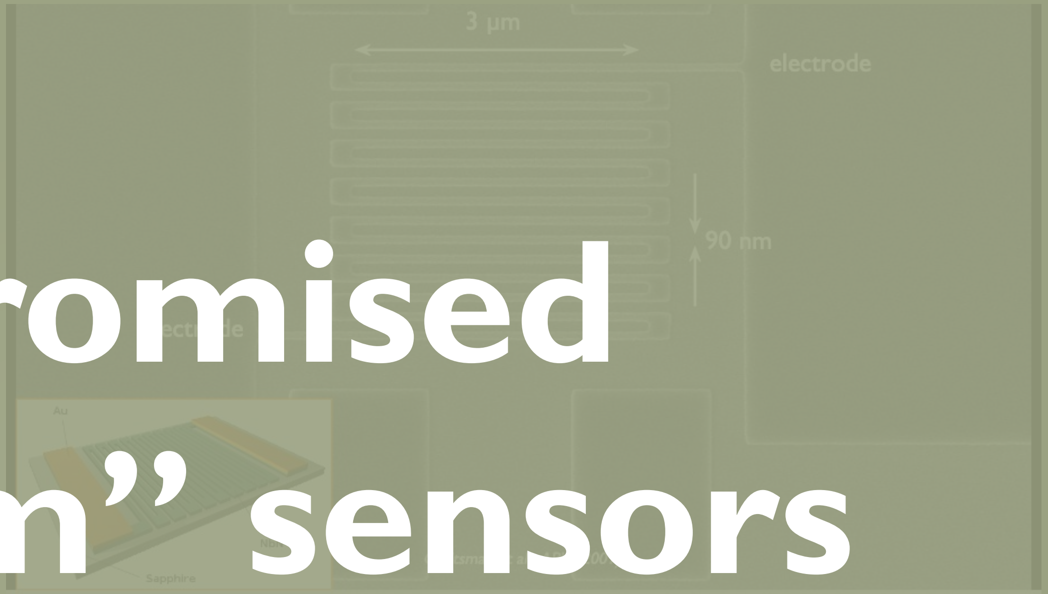
Registered as a very fast pulse

Berggren, 2020

Superconducting Nanowire Single Photon Detectors (SNSPDs)

Take a thin meander of superconducting wire and bias it near its transition point.



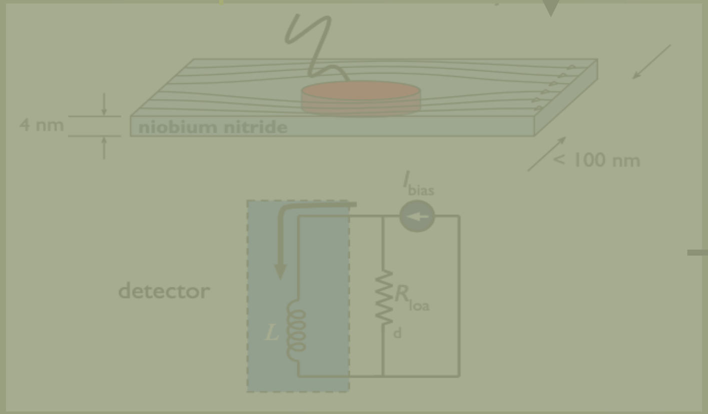


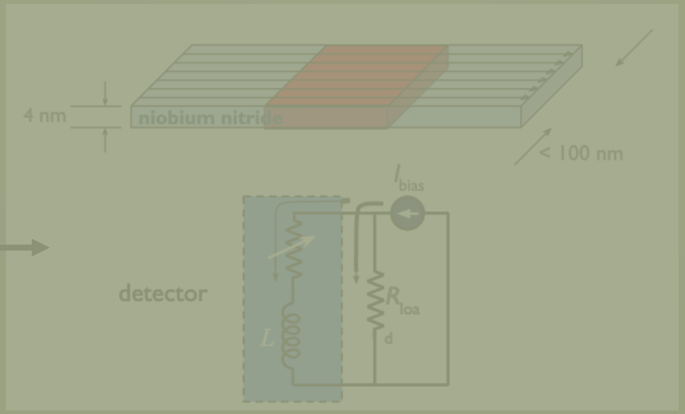
800x500 pixel camera, NIST 2023

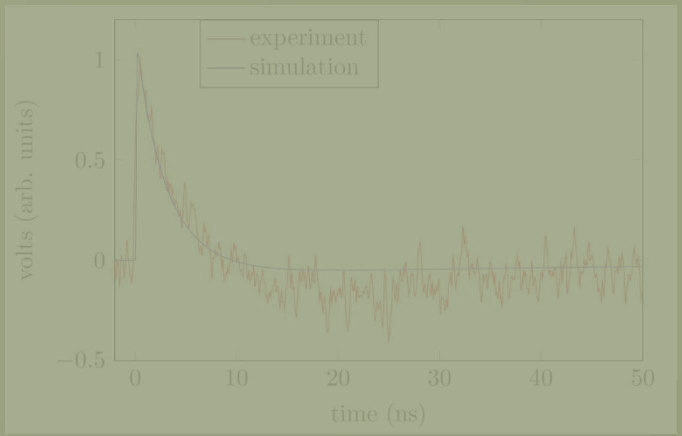
You promised "quantum" sensors

Cools back

Absorbs a photon







Forms a hotspot and diverts current

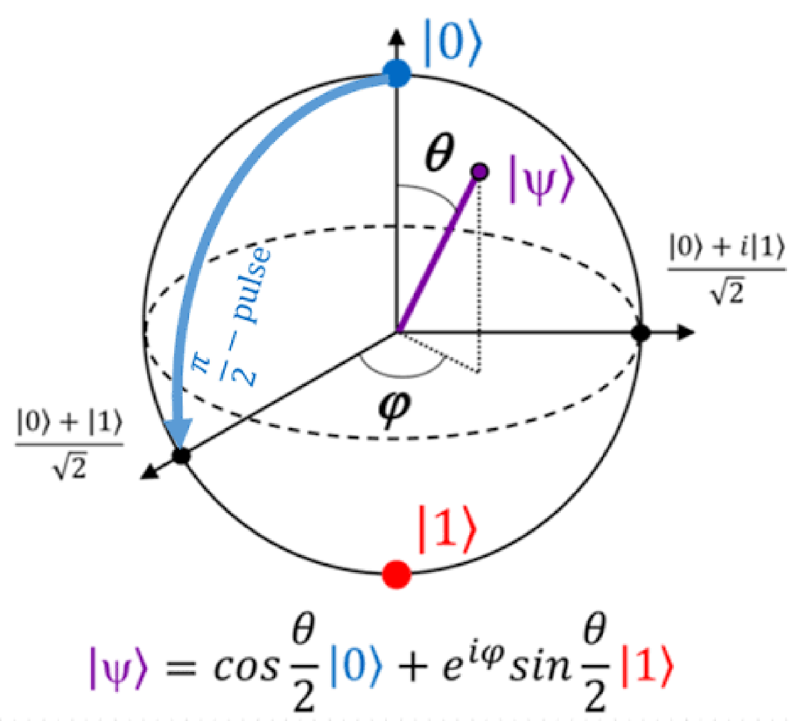
Registered as a very fast pulse

Qubits?

Classical bit 0⟷1

n bits = need to provide n pieces of information e.g. 01

Bloch Sphere



Quantum Bit (qubit) |0⟩⟷ |1⟩

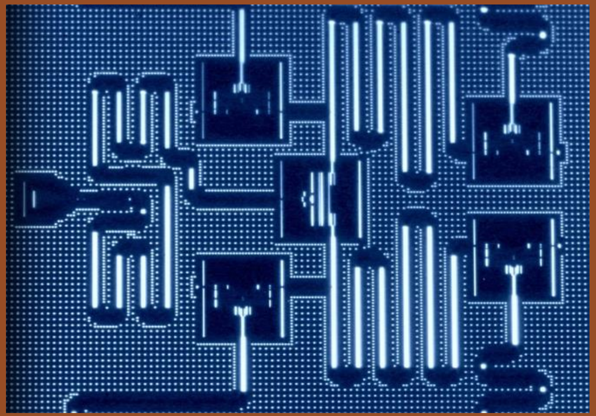
Can be modeled as a 2-state artificial atom

n qubits = 2^n amplitudes describe state

e.g. $|\Psi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$

Aside: why do people care about qubits?

Because one can entangle, superpose, and interfere these states!


IBM chip 2017

$$H|0\rangle = \frac{|0\rangle+|1\rangle}{\sqrt{2}} \qquad H|1\rangle = \frac{|0\rangle-|1\rangle}{\sqrt{2}}$$

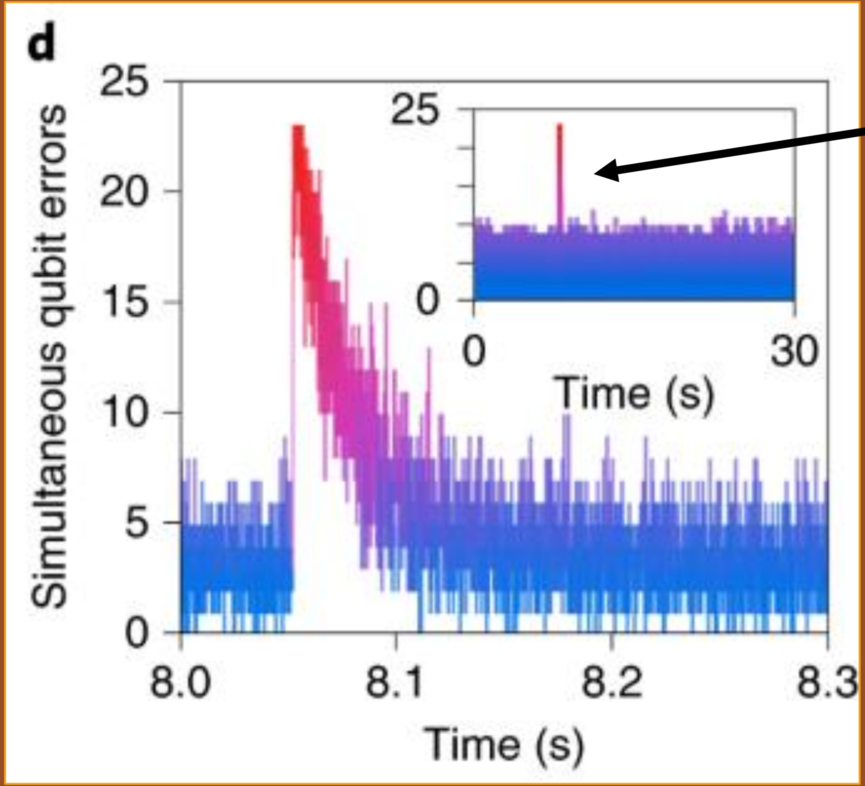
Hadamard operation

$$HH|0\rangle = \frac{1}{2}[(|0\rangle+|1\rangle)+((|0\rangle-|1\rangle)] = |0\rangle$$

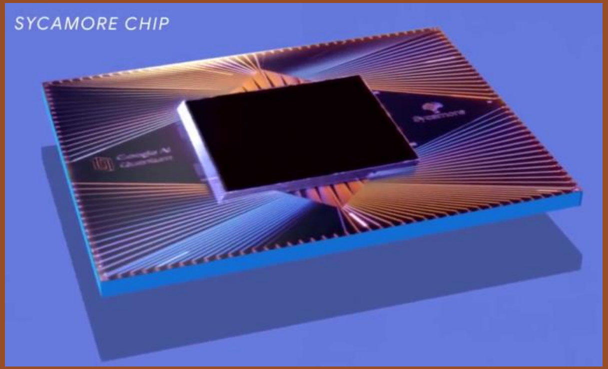
Amplitudes cancel

Now imagine you get hundreds of qubits and can do more complicated gate operations (basically matrix multiplication) → **carefully build up amplitudes you care about and suppress ones you don't want**

Correlated events & cosmic impacts

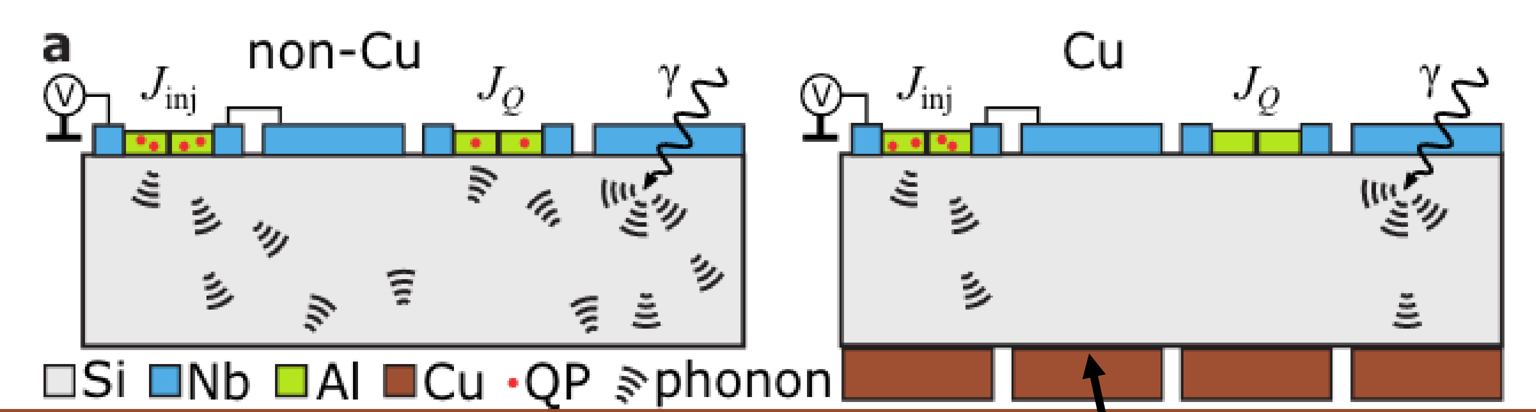


McEwen et al. 2021



Google qubit processor shows **simultaneous errors** across the entire chip. Traced to radiogenic and cosmogenic backgrounds (e.g. **muons**)

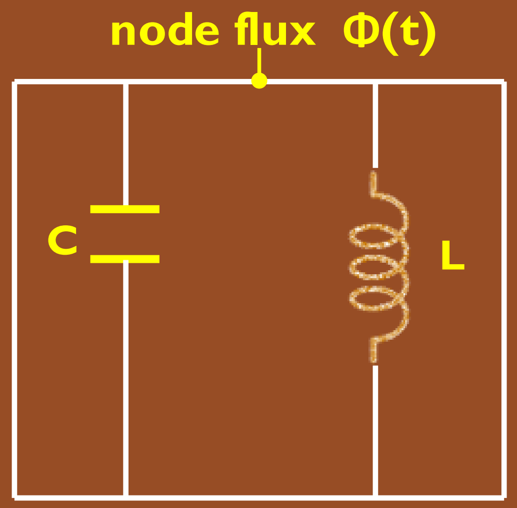
Iaia et al. 2022



Phonons are already a known problem!
One mitigation strategy is to use normal metal traps to soak up phonons

Ok, how do we build a qubit?

Parallel LC resonator



$$\Phi = \int_0^t V(t)dt$$

general circuit coordinate

Energy stored in each element

Capacitor energy ("kinetic")

$$V = QC \qquad E_C = \frac{Q^2}{2C} = \frac{1}{2}C\dot{\Phi}^2$$

Inductor energy ("potential")

$$V = L\frac{dI}{dt} \qquad E_L = \frac{\Phi^2}{2L}$$

$$\Phi = LI$$

Mechanical analogy

mechanics		**circuit**
position x	→	flux Φ
momentum p	→	charge Q
mass m	→	capacitance C
spring k	→	1/inductance 1/L

Looks like a harmonic oscillator

$$H = \frac{\Phi^2}{2L} + \frac{Q^2}{2C} \Rightarrow \frac{\Phi^2}{2L} + \frac{1}{2}C\dot{\Phi}^2$$

Quantization

The circuit variables flux Φ and charge Q form a canonical conjugate pair → **promote to operators**

*can understand this using Lagrangian and from definition of conjugate momentum for a generalized coordinate

$$[\hat{\Phi}, \hat{Q}] = i\hbar$$

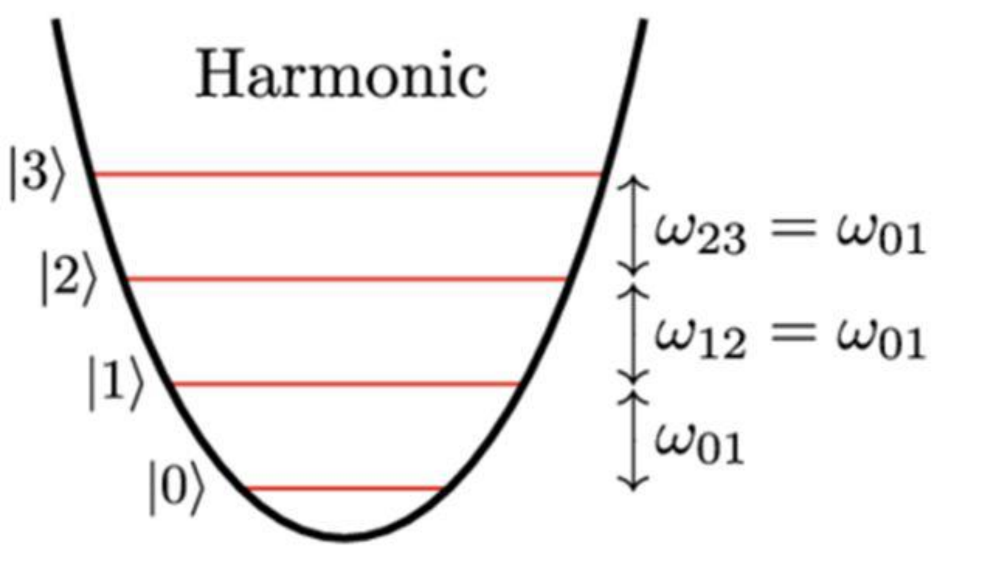
$$H = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C}$$

define and construct annihilation and creation operators just like the mechanical case

$$H = \hbar\omega\left(\hat{n} + \frac{1}{2}\right)$$

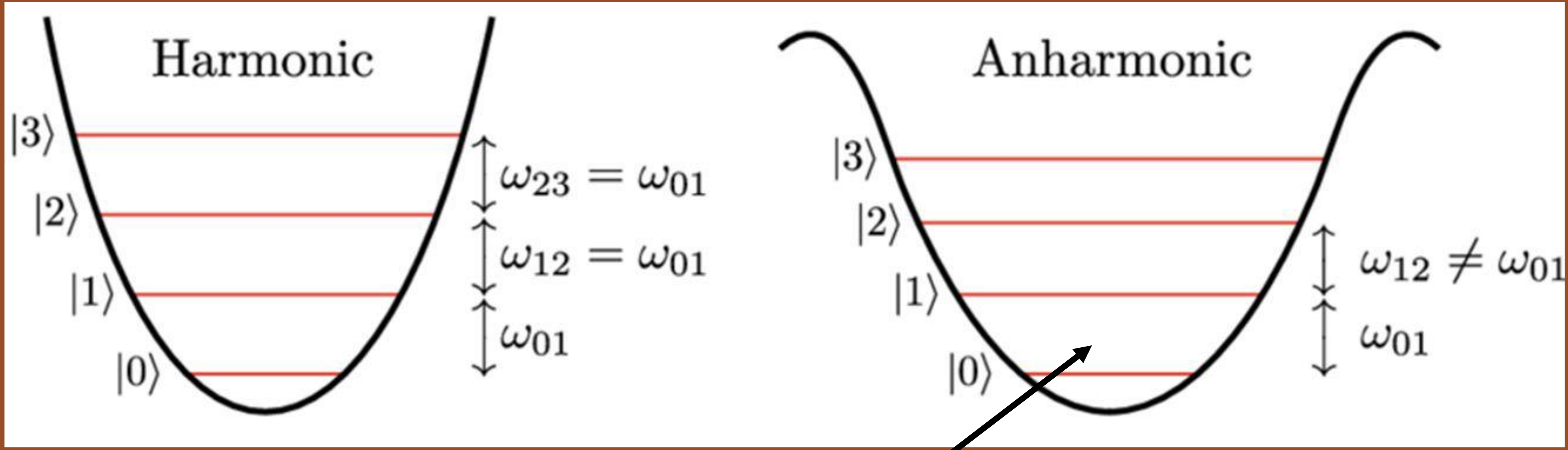
Energy level spacing ($\hbar\omega$)

$a^\dagger a$ ($\hat{n}$)



If a photon can drive |0⟩→|1⟩, it is also resonant with |1⟩→|2⟩ ☹ Not a stable isolated 2 state system to build a qubit out of

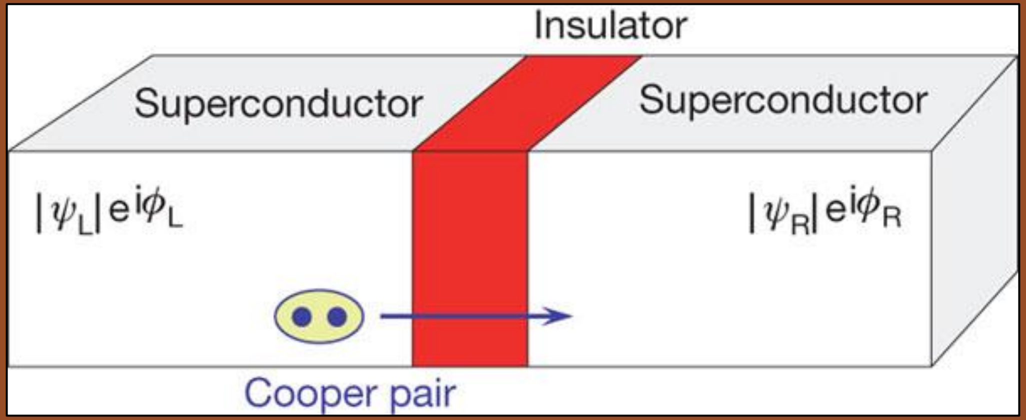
(an)harmonicity



We need to modify the potential shape to get a system where the energy levels spacings are changing

Hmmm… have we come across a **non-linear capacitive or inductive element before?**

Josephson Junctions II



Current relationship: $I = Ic \sin\phi$ where ϕ is the phase difference between sides

$$\Rightarrow \frac{dI}{dt} = I_c \cos\phi \frac{d\phi}{dt}$$

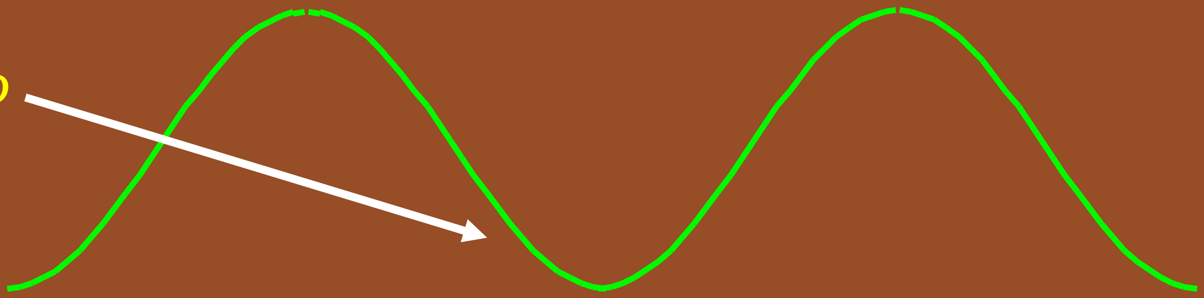
Voltage relationship: $V = \phi_0 \frac{d\phi}{dt}$

$$\Rightarrow V = \frac{\phi_0}{I_c \cos\phi} \frac{dI}{dt}$$

Looks a lot like $L\frac{dI}{dt}$

Ok, now let's plug this into our Hamiltonian (remember, "P = IV")

$$U_J = \int IV = -I_c\phi_0 \cos\phi = -E_J \cos\phi$$



Cosine potential → anharmonic!

The Hamiltonian

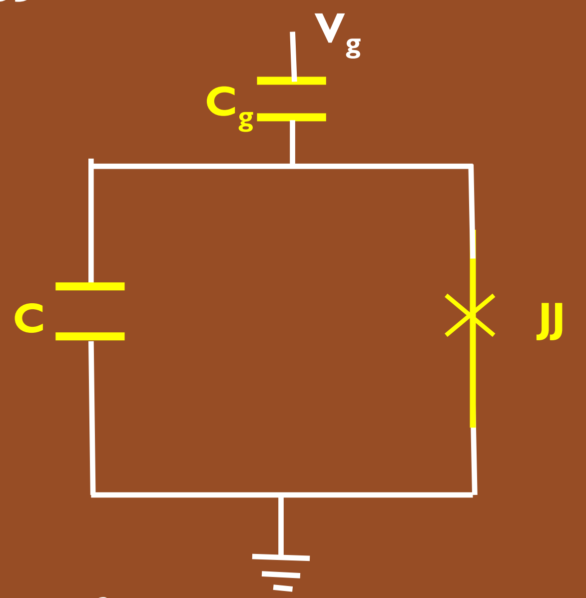
Let's put everything together (with a small change):

$$H = \frac{(Q - Q_g)^2}{2C_\Sigma} - E_J \cos\phi$$

Total capacitance now

Quantization business again $[\hat{\phi}, \hat{n}] = i$

Parallel JJ-C network



(We can use dimensionless charge using $\hat{Q} = 2e\hat{n}$ since 2e in a Cooper-pair, and defining $E_C = \frac{e^2}{2C_\Sigma}$ we get)

$$\hat{H} = 4E_C\left(\hat{n} - n_g\right)^2 - E_J \cos\hat{\phi}$$

Charge induced by voltage on gate capacitor ("gate charge")

Spectrum of E_J/E_C

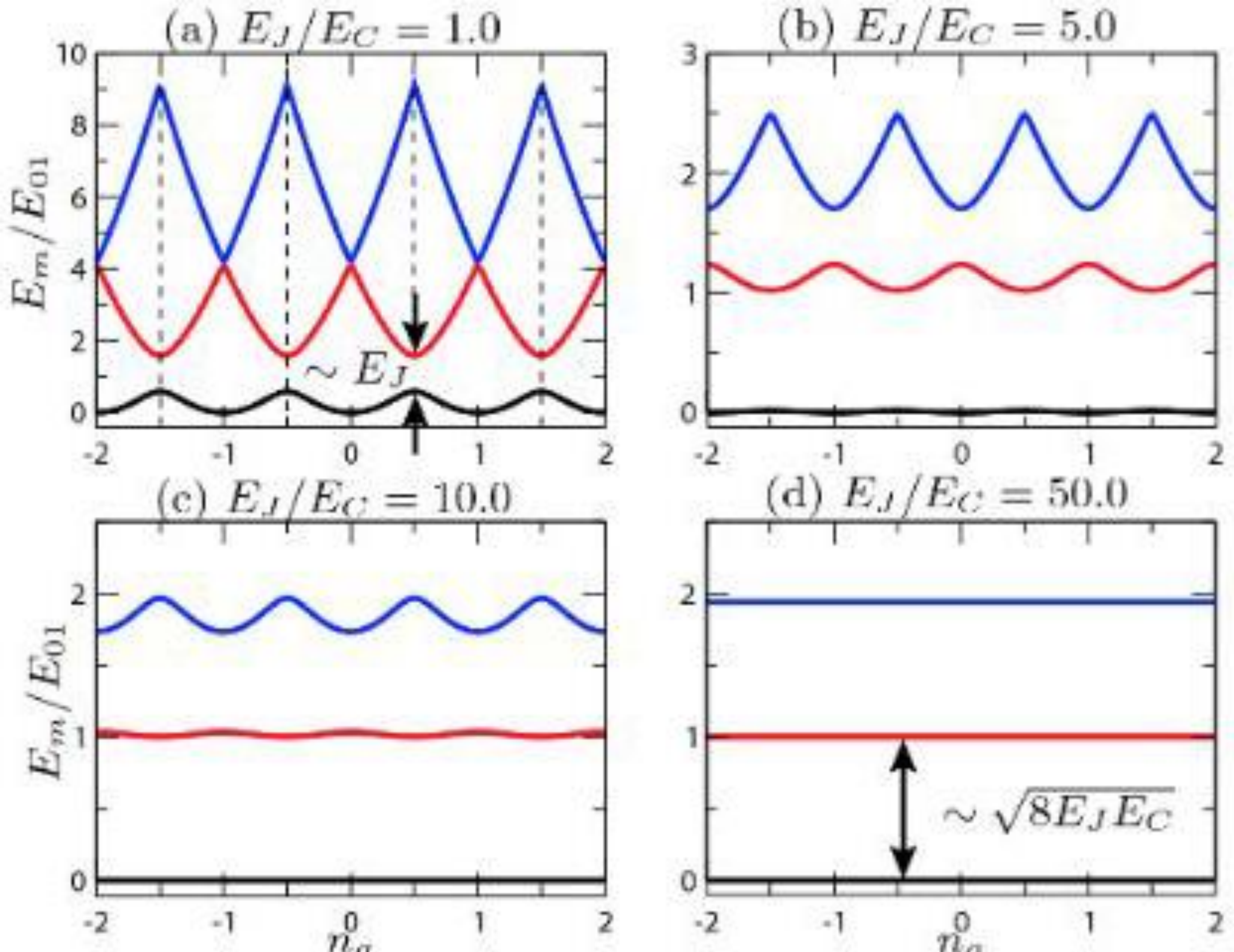
Let's diagonalize the Hamiltonian and look at energy levels as a function of n_g

Strong dependence on E_J/E_C ratio

$E_J/E_C \sim 1$ or $<< 1$ → charge regime

$E_J/E_C \sim 10$ → charge sensitive regime

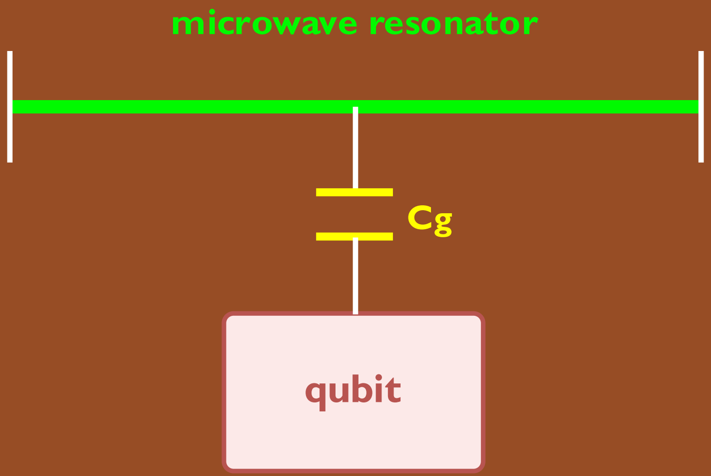
$E_J/E_C >> 1$ → transmon regime

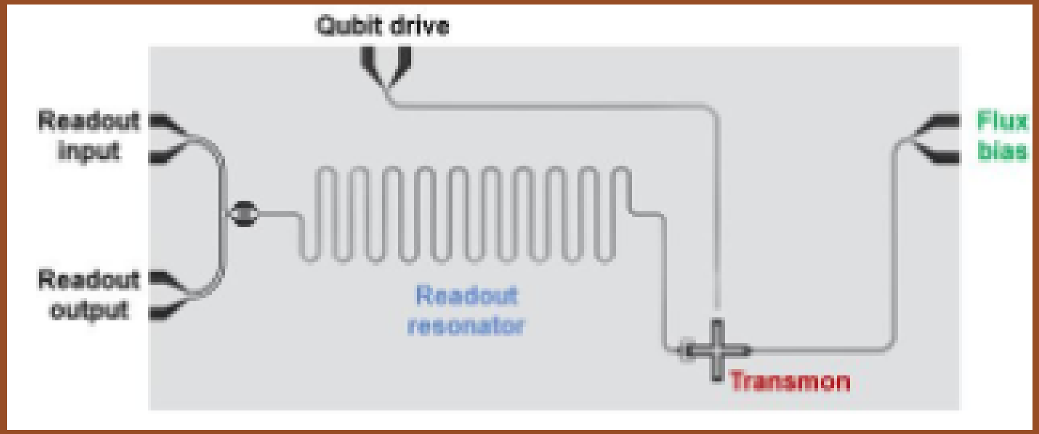


Schuster, 2007

Coupling to the world

Qubit + resonator





Jaynes–Cummings model

$$\hat{H} = \hbar\omega_r\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) + \frac{\hbar\omega_q}{2}\sigma_z + \hbar g(\hat{a}\sigma_+ + \hat{a}^\dagger\sigma_-)$$

Resonator of frequency ω_r, modeled as quantum harmonic oscillator

Qubit of frequency ω_q, effective 2 level system, modeled now with Pauli matrix

Interaction of strength "g": exchange an excitation between the resonator and qubit.

Dispersive Interaction

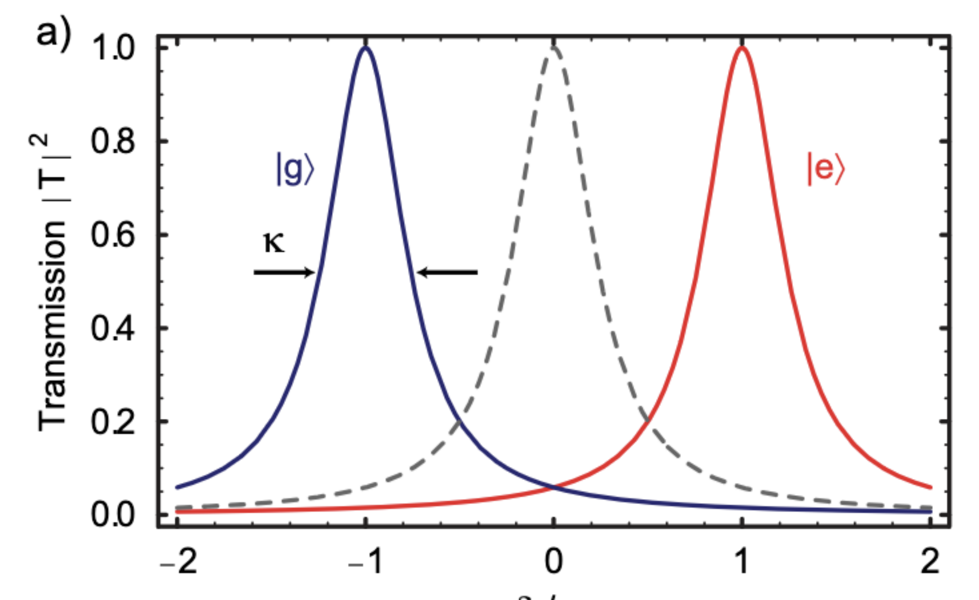
In the limit that the qubit and resonator frequencies are sufficiently distant and the coupling is "weak" (i.e. $g \ll (\Delta = |\omega_r - \omega_q|)$) can simplify to:

$$\hat{H} \approx \hbar(\omega_r + \frac{g^2}{\Delta}\sigma_z)(\hat{a}^\dagger \hat{a} + \frac{1}{2}) + \frac{\hbar\omega_q}{2}\sigma_z$$

Resonator frequency shifts depending on qubit state!

Qubit term

Upshot → can monitor the qubit by measuring the resonator frequency/phase



Schuster, 2007

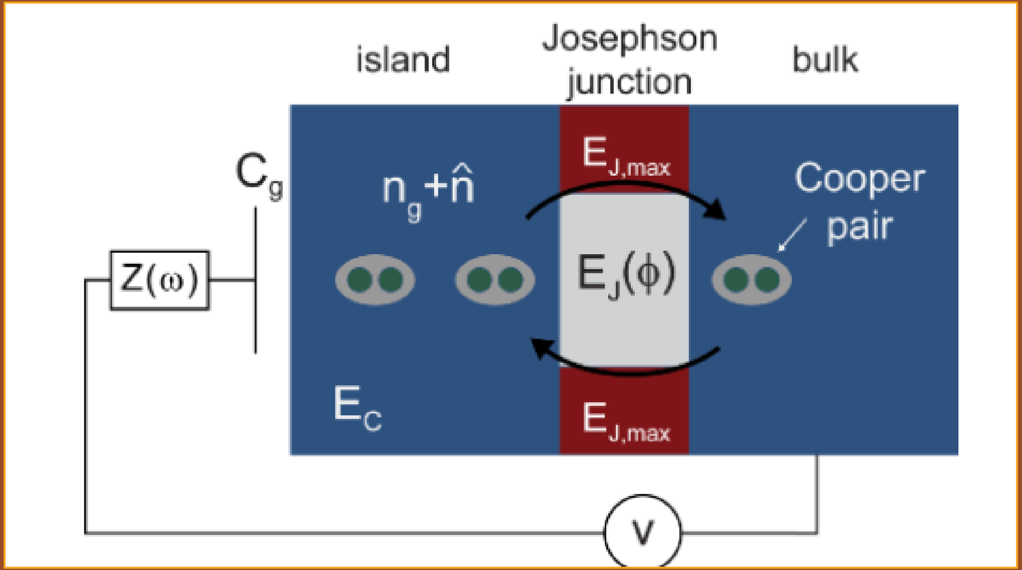
Dispersive Interaction

That was the world's briefest intro to Circuit Quantum Electrodynamics ("Circuit QED")

Go read e.g. Blais et al. (arxiv.org/pdf/2005.12667) or Roth et al. (arxiv.org/pdf/2106.11352) for recent reviews on everything about qubits, cQED, engineering and use cases

★ Parity

- Relevant D.O.F: **# of Cooper pairs on the island**
- What happens when single quasiparticles tunnel → **shift by a half charge**



Walraff et al. 2006

$$\hat{H}_{\mathrm{CPB}} = 4E_C\left(\hat{n} - n_g + \frac{P-1}{4}\right)^2 - E_J\cos\hat{\varphi}.$$

Charging energy (energy to add another Cooper pair to the island): $(2e)^2/2C_g$

Josephson energy

Parity: **$\pm$1, measure of number of electrons (even/odd)) that have traversed the junction**

Dimensionless *offset charge*: $C_gV_g/2e$

Making a detector

Look at energy levels of H_{CPB}

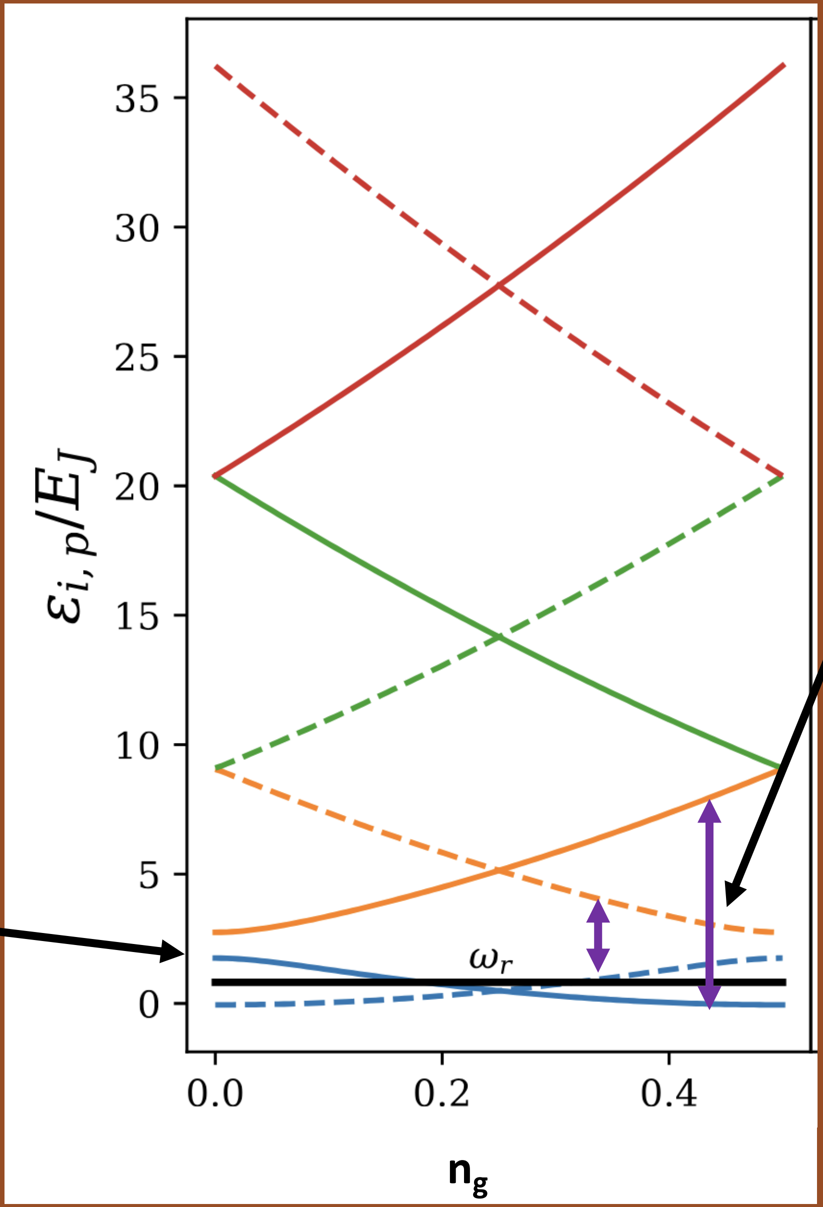
---------- Odd State

———— Even State

Note curvature of bands
Interpretable as a capacitance!

$$C_i = -\frac{C_g^2}{e^2}\frac{\partial^2 E_i}{\partial n_g^2}$$

Make a O(GHz) LC resonator and couple this qubit to it – O(MHz) shift from this changing capacitance with tunneling

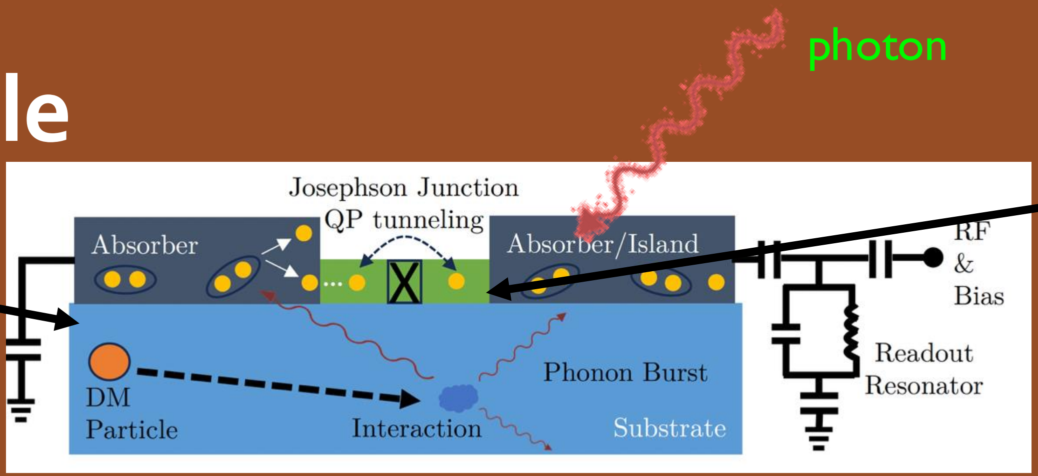


Difference in transition energy from 0 to 1 level depending on this "parity" state

Upshot: monitor the parity state shifts. Tunneling rate gives you handle on number of quasiparticles created

★

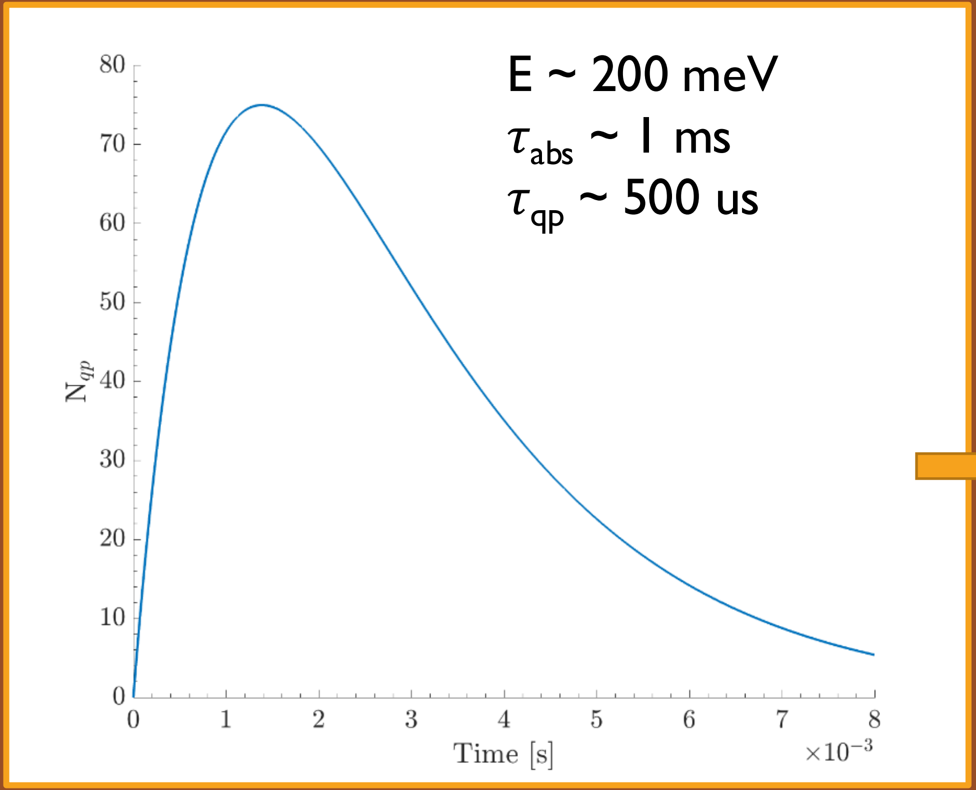
Detection Principle

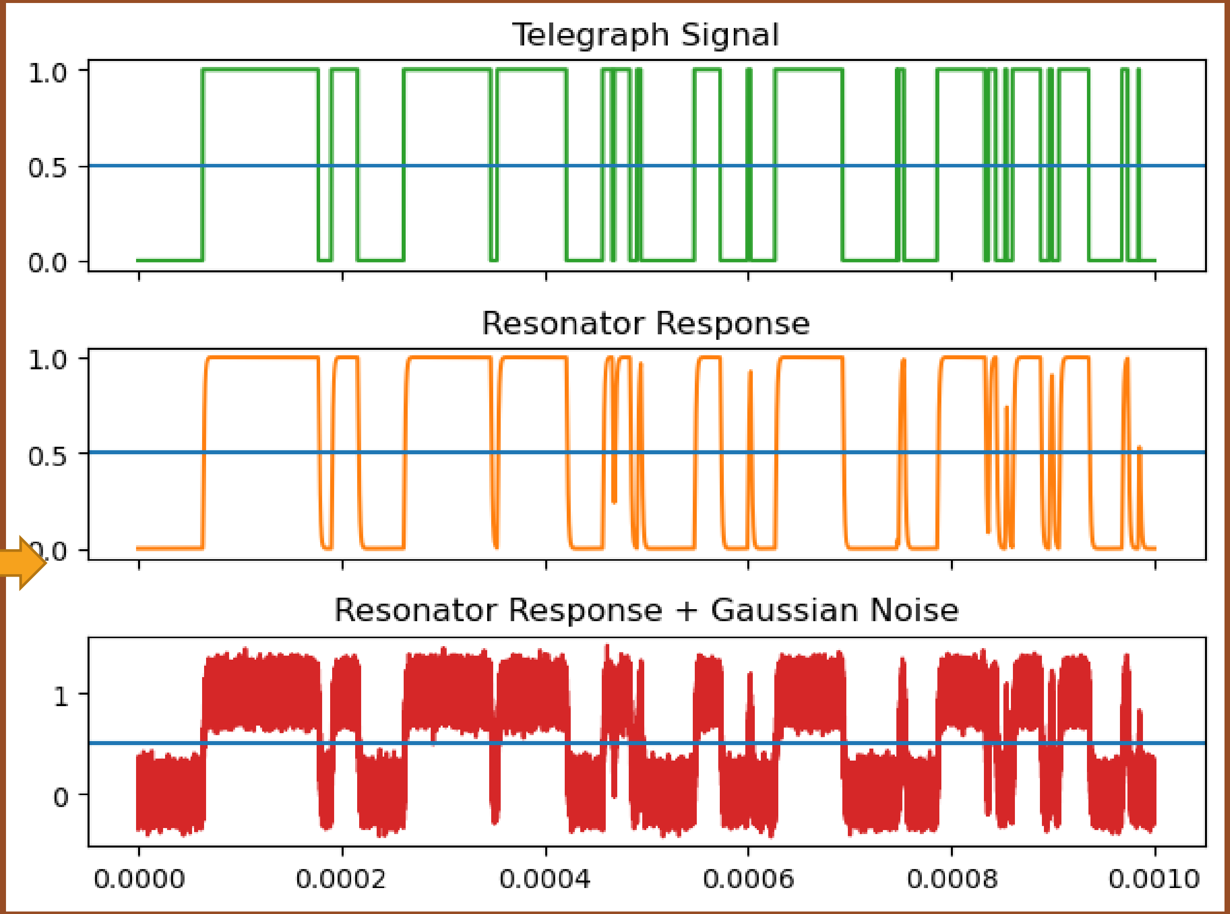


For phonons couple it to a large **substrate**

Sub-eV sensitivity will require **low-Tc material** junctions with smaller gap than Aluminum

Quasiparticle production in absorber



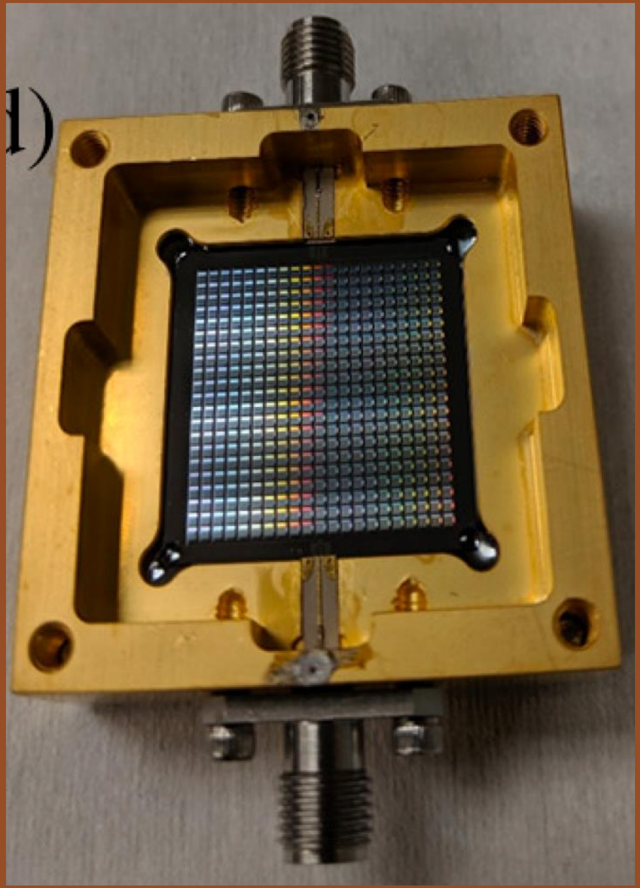


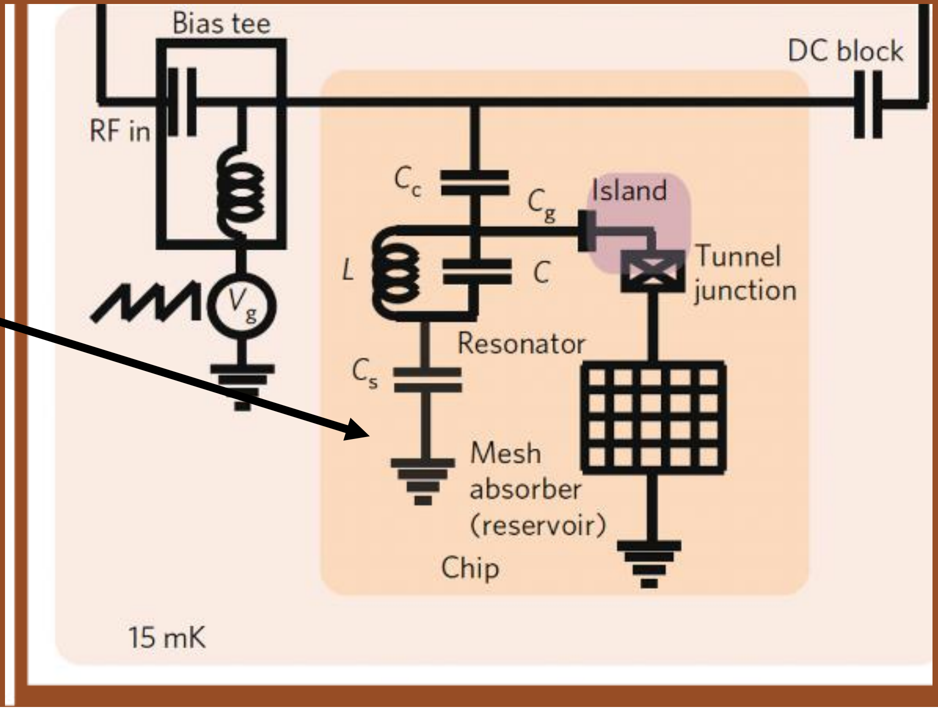
★

Quantum Capacitance Detectors

Shaw et al. 2009, Echternach et al. 2017

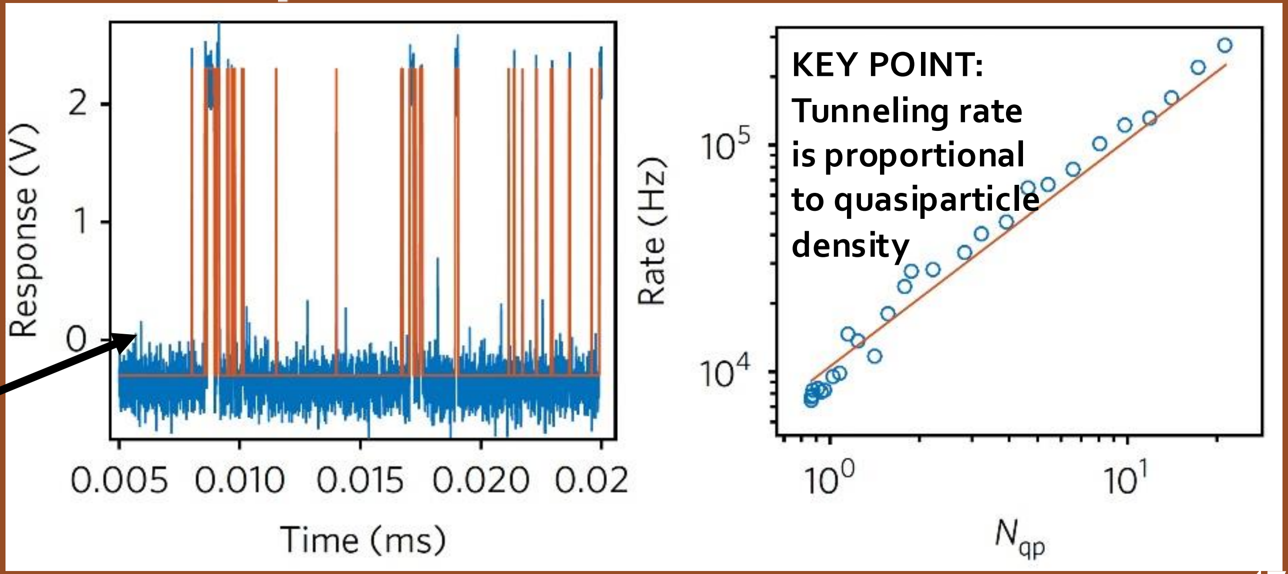
Couple JJ structure to a large **absorber** and a **resonator**. Changing capacitance affects LC of resonator





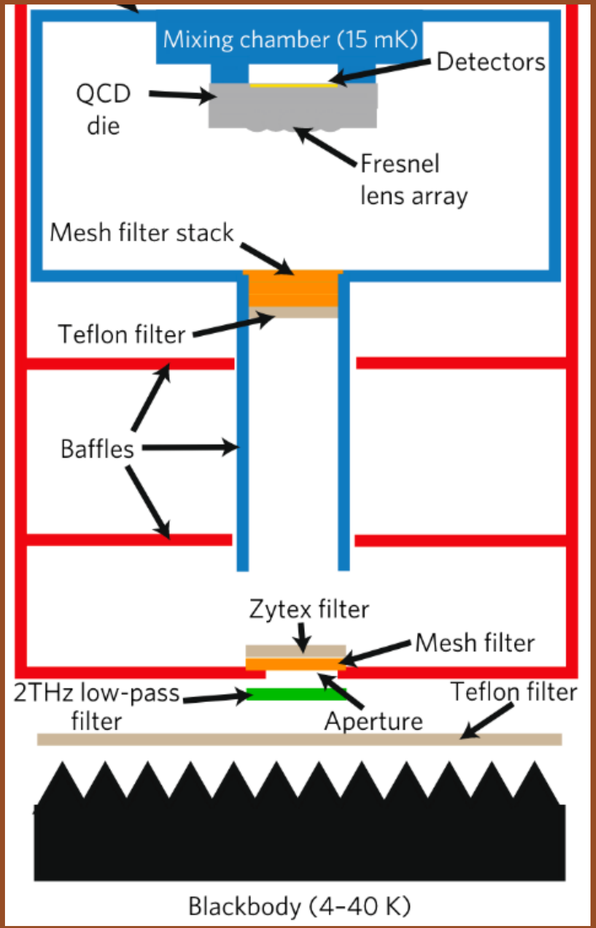
441 QCD device
Demonstrated at JPL for THZ photon counting

Time trace of switch between even and odd parity states

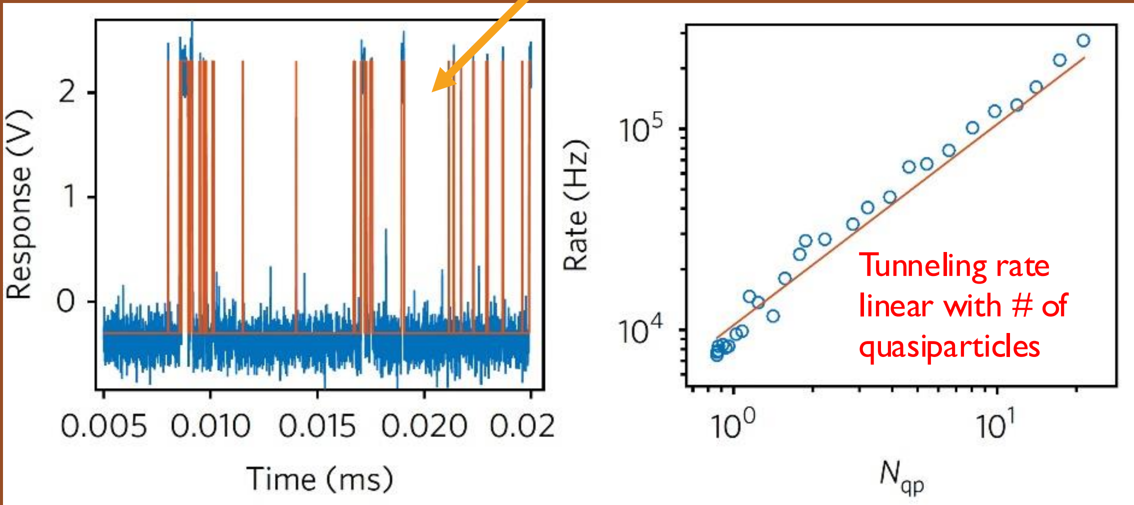


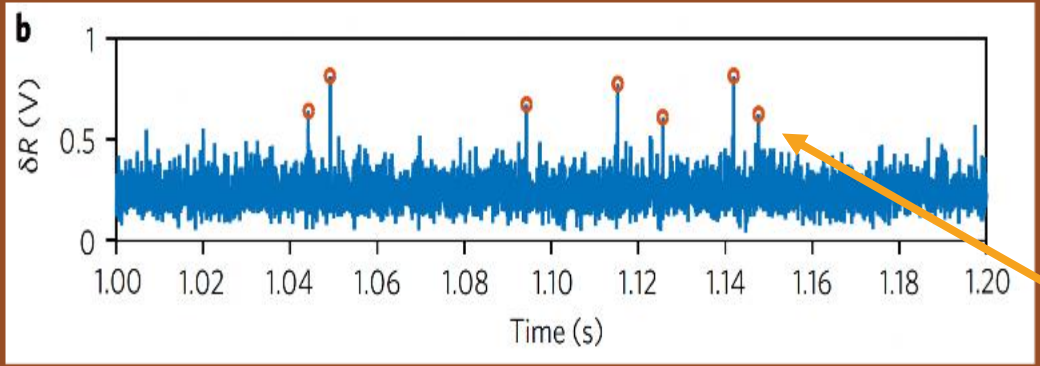
Far-IR Photon Counting Setup

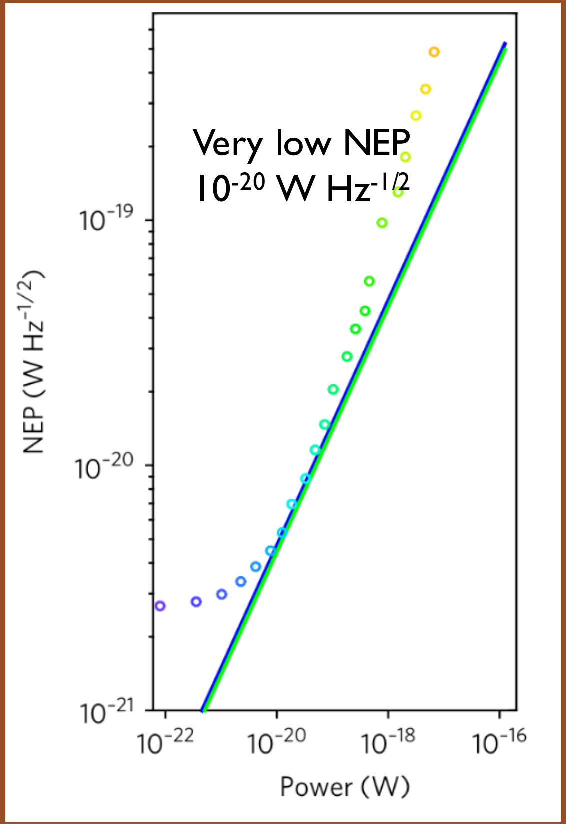
1.5 THz (7 meV) FIR illumination setup



Tunneling trace of QP events



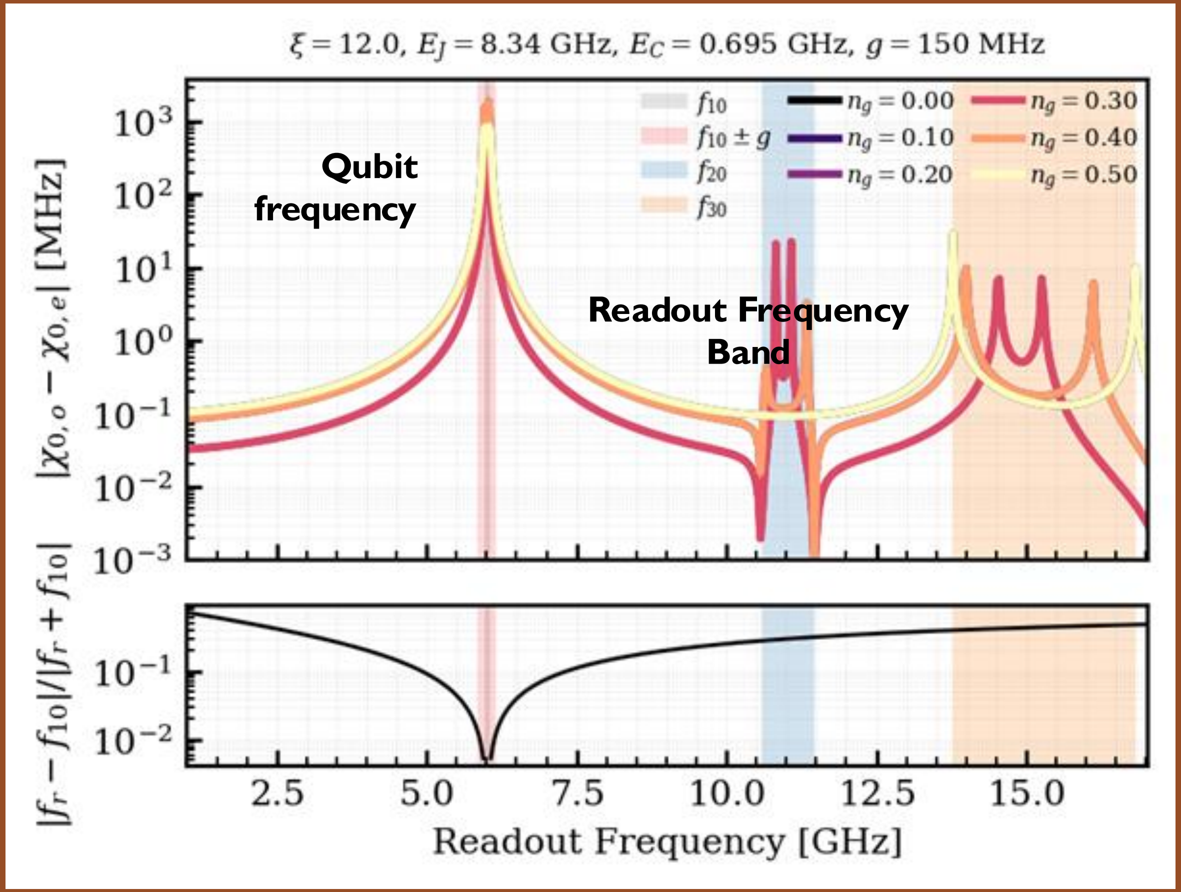


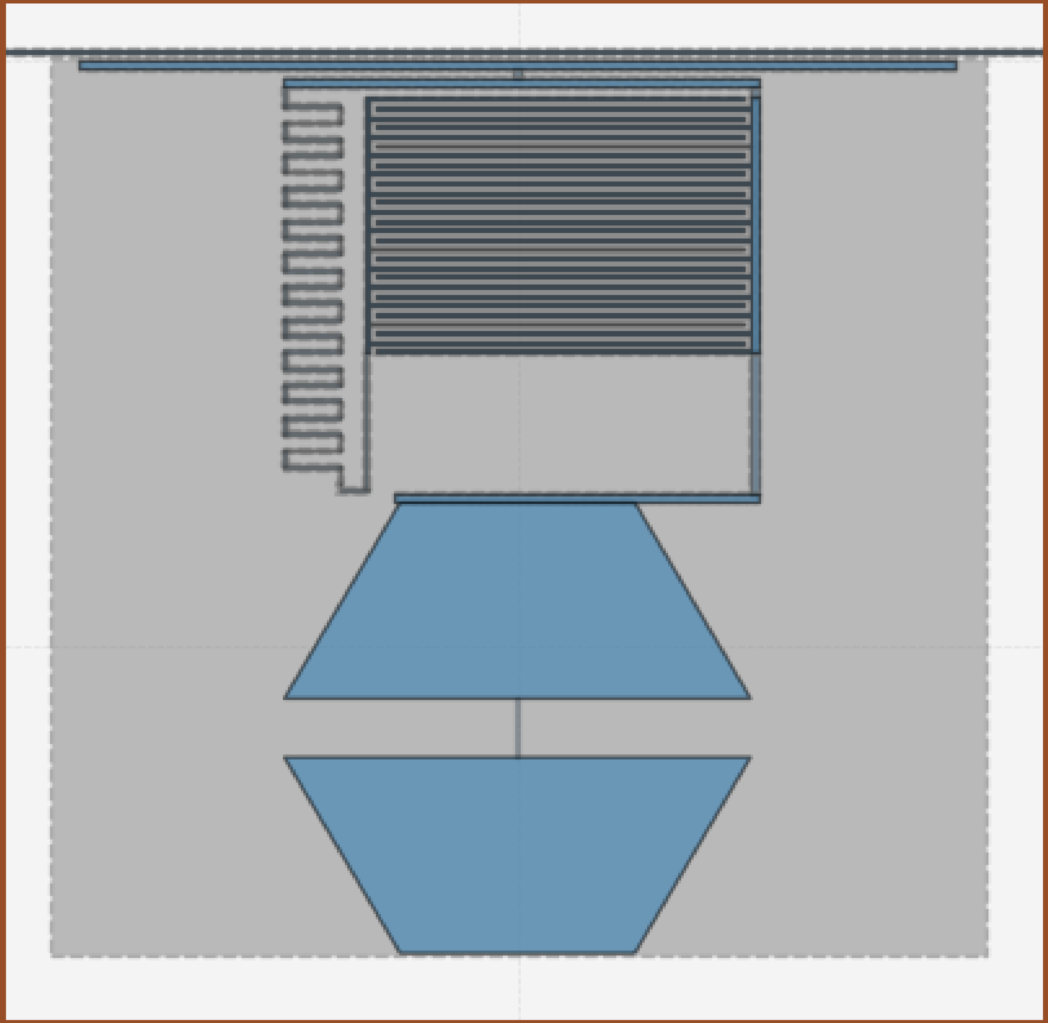


Can look for periods of high tunneling → counting single photons!

Inferred quiescent quasiparticle density < 1/um^3

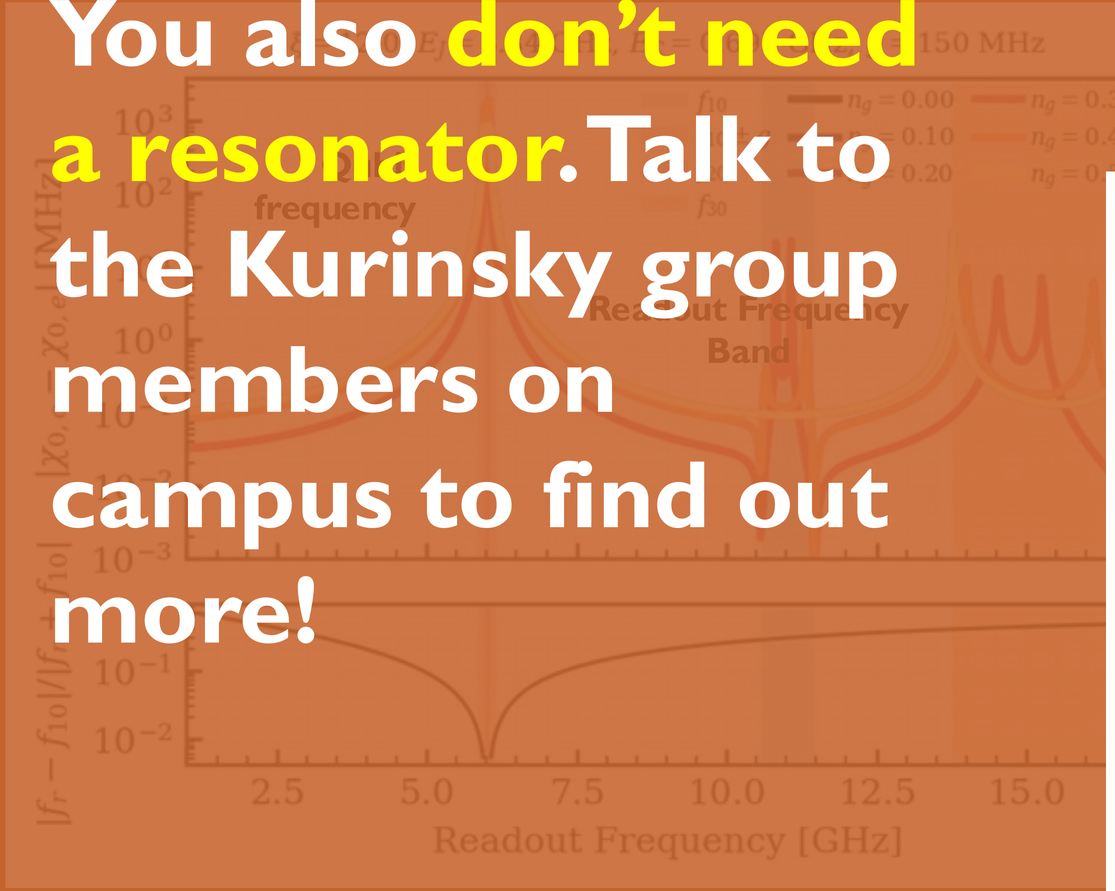
★ Phonon sensitive Quantum Parity Detectors (QPD)





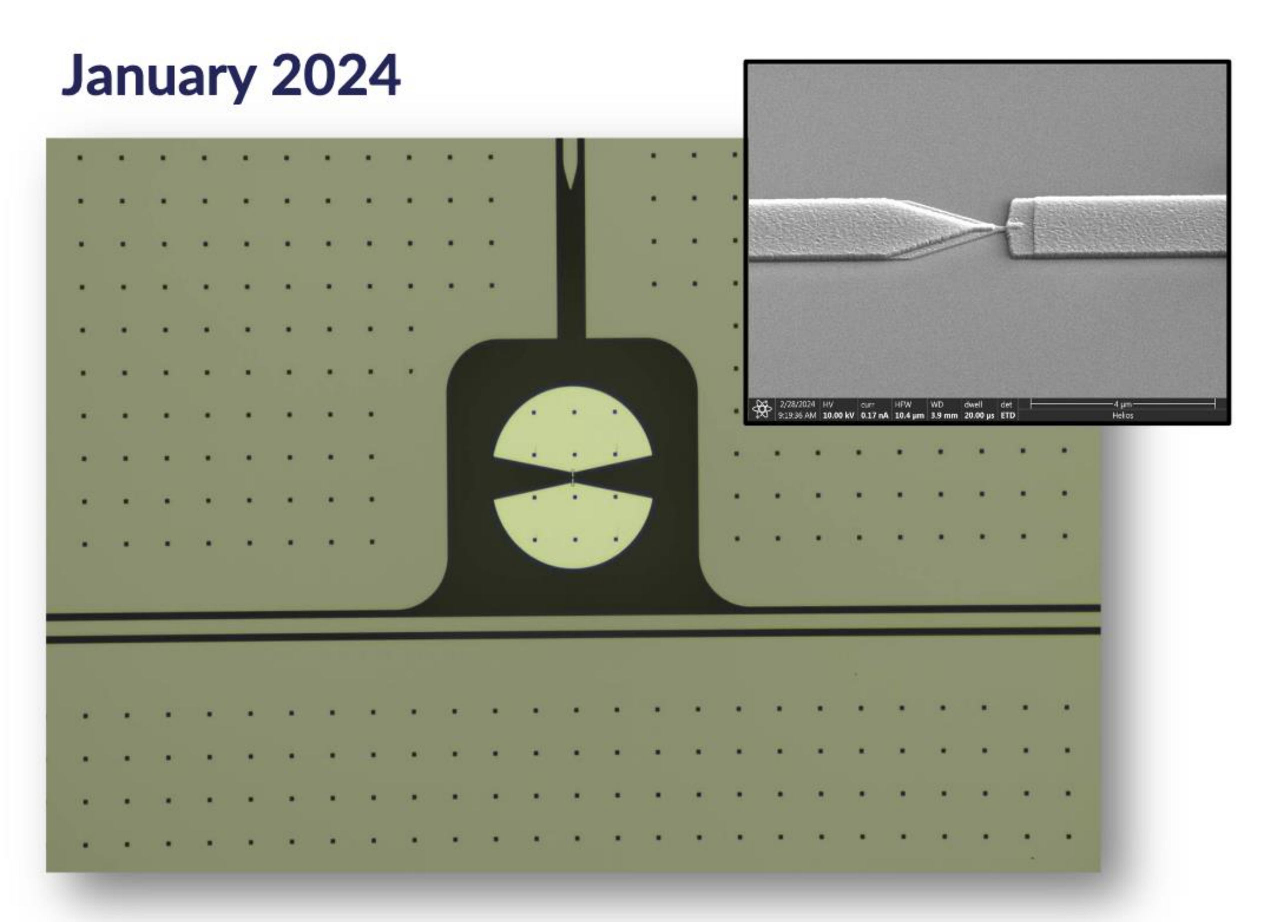
Judicious choice of **resonator frequency location**, can exploit complex resonator+qubit physics to directly monitor qubits

Phonon Sensitive Designs Interaction



You also **don't need a resonator.** Talk to the Kurinsky group members on campus to find out more!

Superconducting Quantum Amplifying Transmon (SQUAT)



Judicious choice of **resonator frequency** can exploit complex resonator+qubit phys... directly monitor n in Transmon case

Back of the envelope estimates

Resolution on number of signal transitions →

$$\sigma_S^2 = \left(K \frac{\tau_{qp}}{V} + K^2 \left(\frac{\tau_{qp}}{V} \right)^2 F \right) N_{qp}^r$$

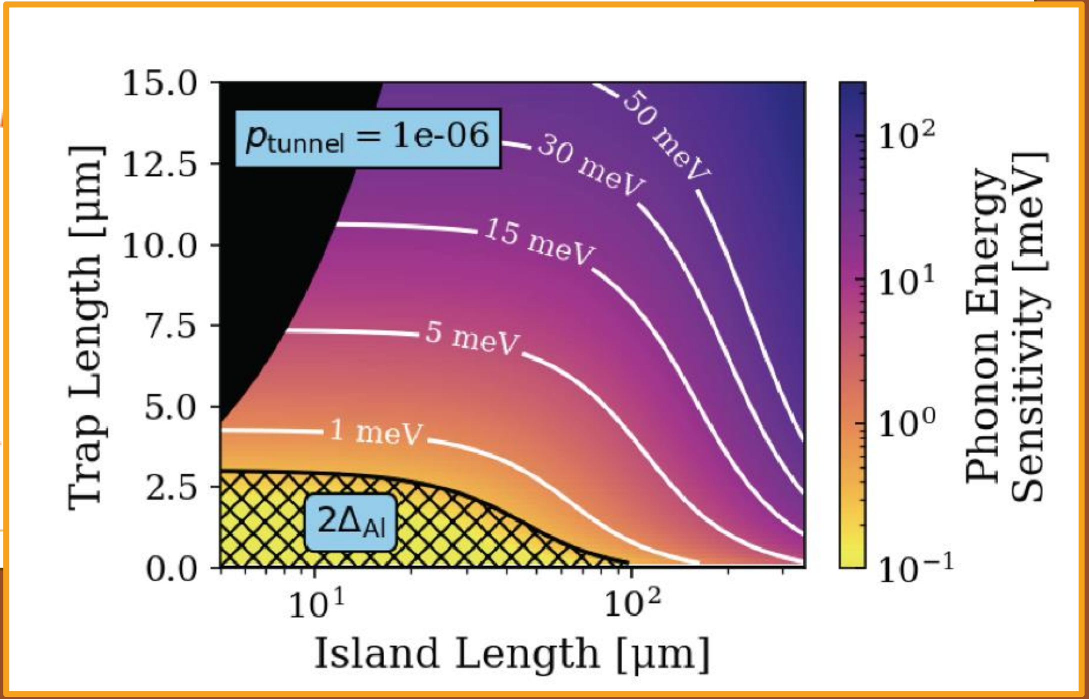
- $\Gamma_{in} = K n_{qp}$
- *Quasiparticle Lifetime*
- *Sensor Volume*
- *Fano Factor ~ O(0.1)*
- *Max no. of qp's generated from energy deposition*
- **Tunneling Shot Noise**
- **Fano Noise**

Expected number of switches → $S = K \frac{N_{qp} \tau_{qp}}{V}$, with $K = \frac{16 E_J k_B T}{\mathcal{N} \Delta h}$

Resolution on number of background transitions →

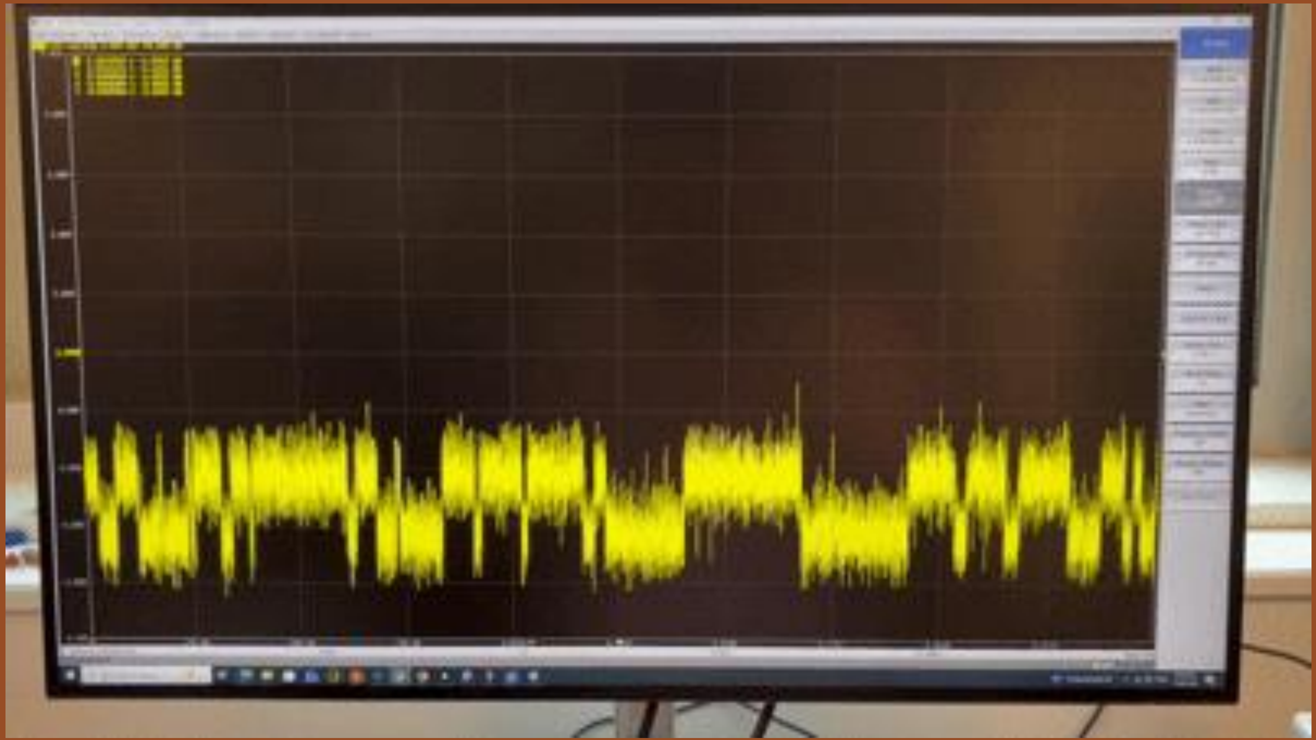
$$\sigma_B^2 = \left(K t_w + 16 \frac{K^2 t_w^2}{V} \right) n_0$$

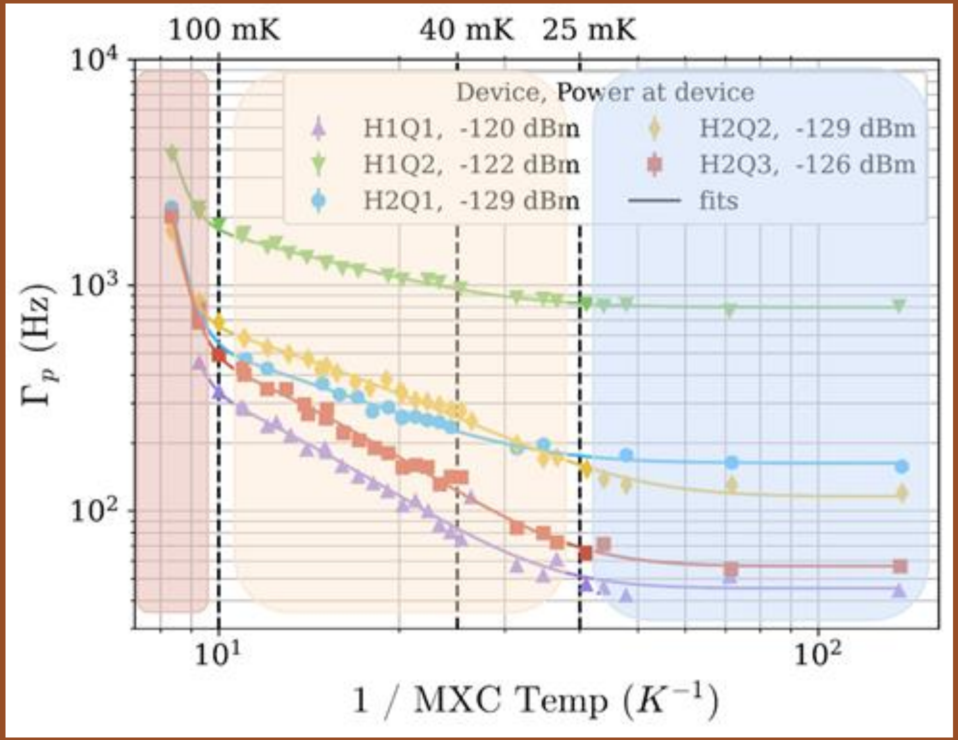
- *Time window*
- **Tunneling Shot Noise**
- **Quiescent Quasiparticle Noise**
- *Quiescent Quasiparticle Density*



Can potentially get down to O(meV) sensor resolutions with **good gap & trap engineering**

★
Recent progress





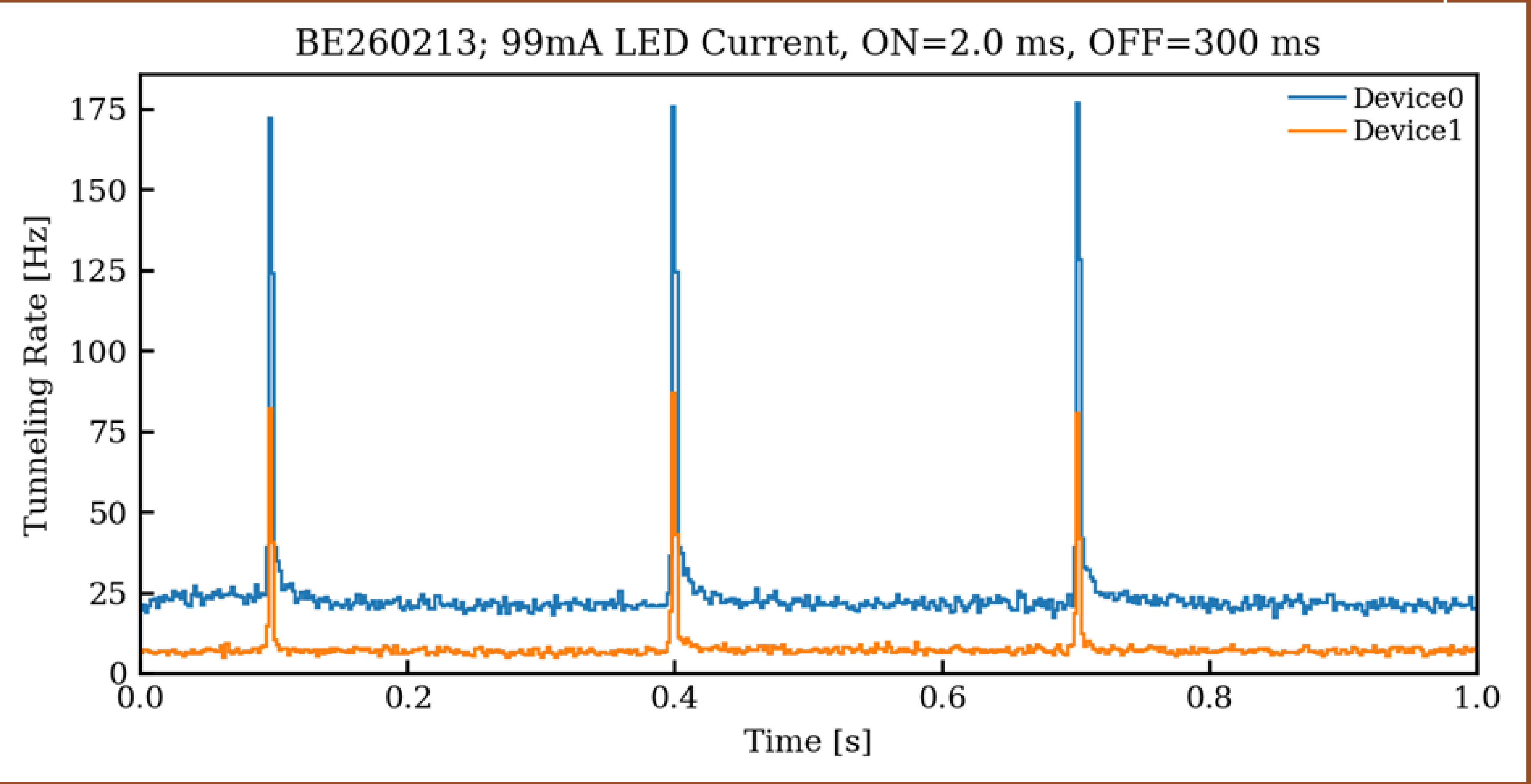
Devices respond to external effects → video of a QPD (Al on Si) being monitored as we **kick the fridge (!)** → note the **spike in the tunneling rate.**

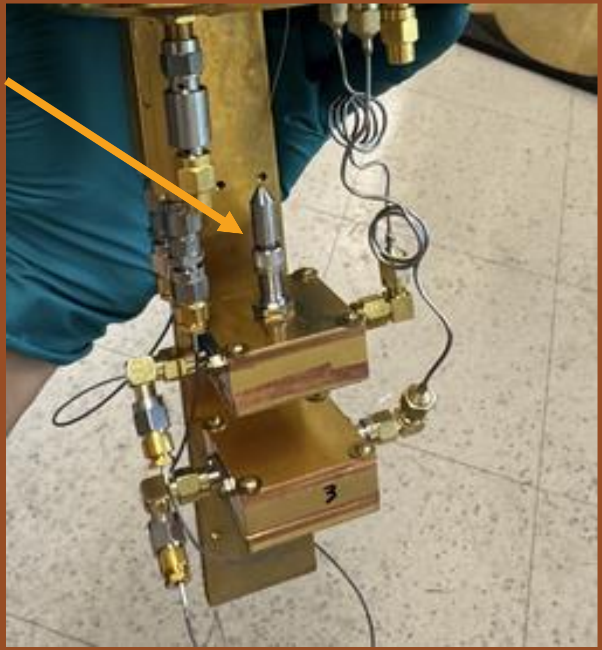
Quiescent tunneling rates of O(Hz) which suggests background quasiparticle density of << 1 um^{-3}

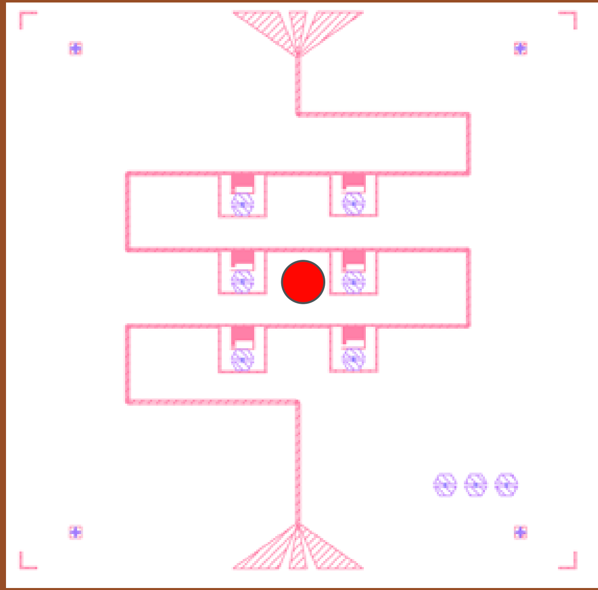
★

Recent progress II

625nm LED spot pointed at center of chip backside, **pulsed at ~3 Hz** with **2.0 ms long flashes** (estimate ~100 keV/pulse)



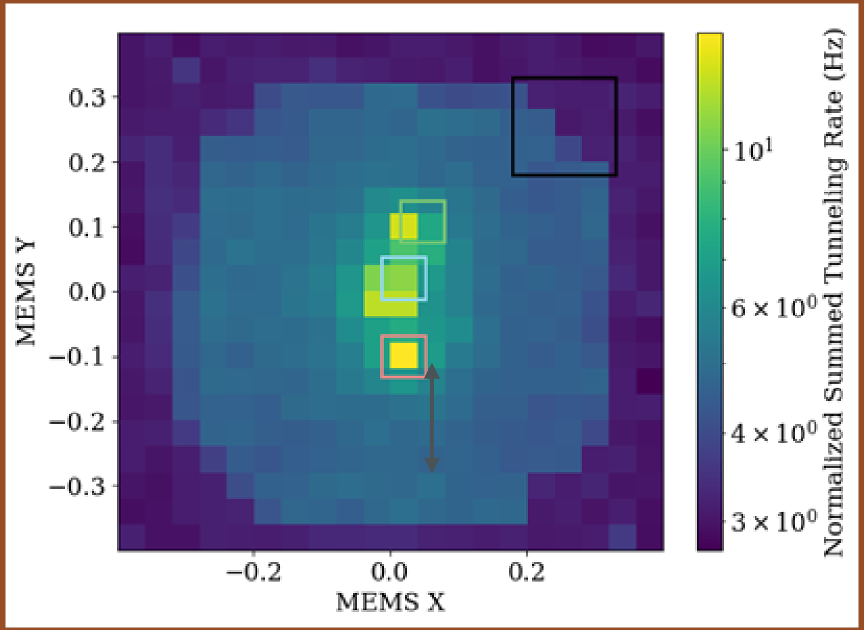


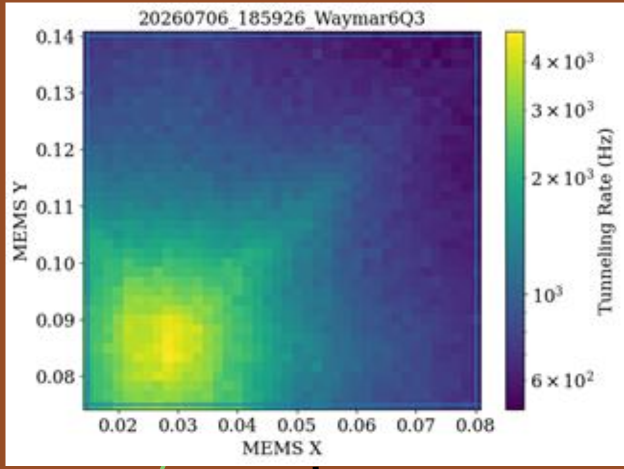


Averaged **6000 pulse trains** and in ~5 ms bins. **Spike in tunnelling rate** coincident with pulsing.

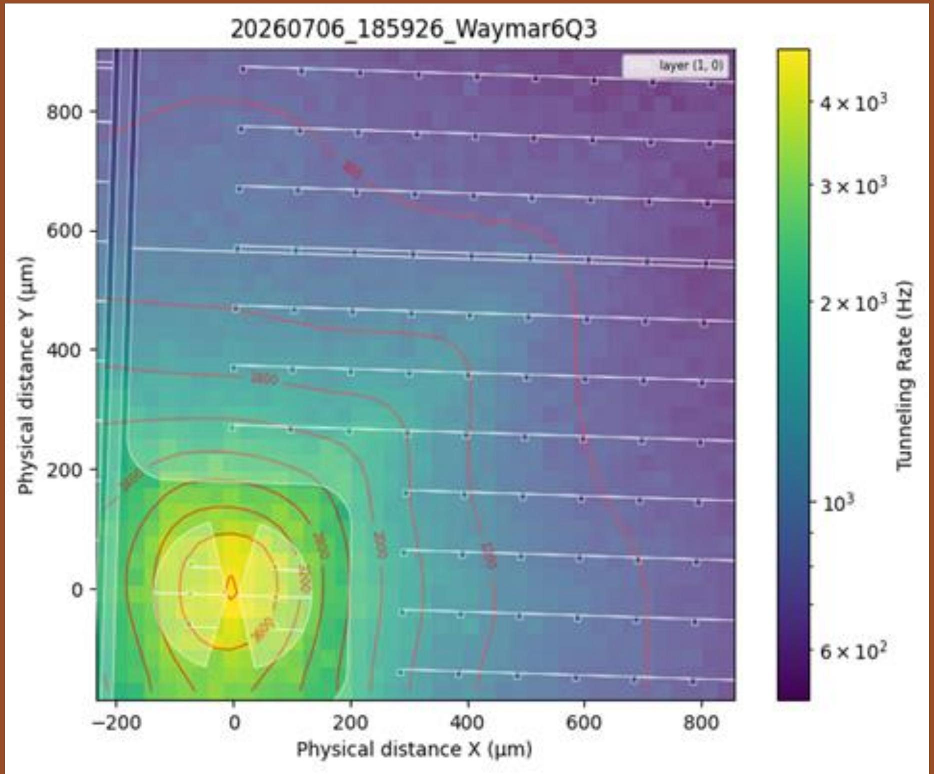
Recent progress III

Scanning with **constant** 625 nm light on **backside**, looking at resulting increases in SQUAT tunneling rate

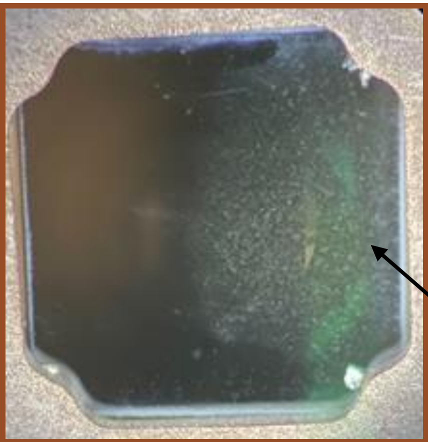




Phonon sensitivity structure visible:



Chip backplane: (target for light)



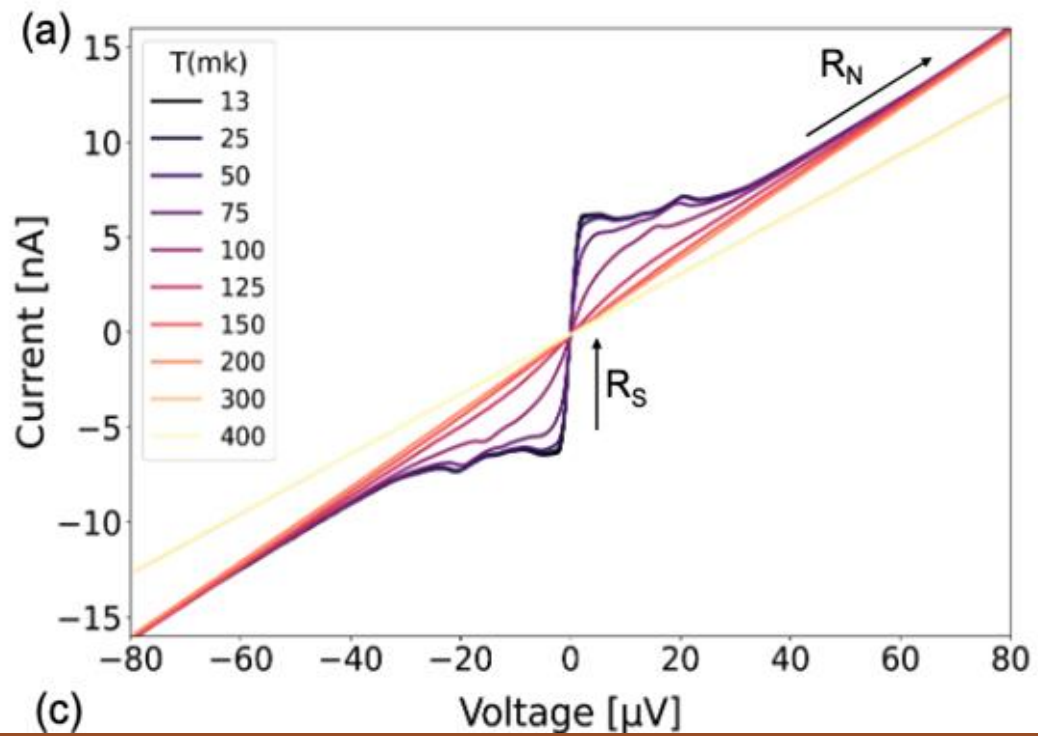
Silica dust *(debris from laser dicing)*

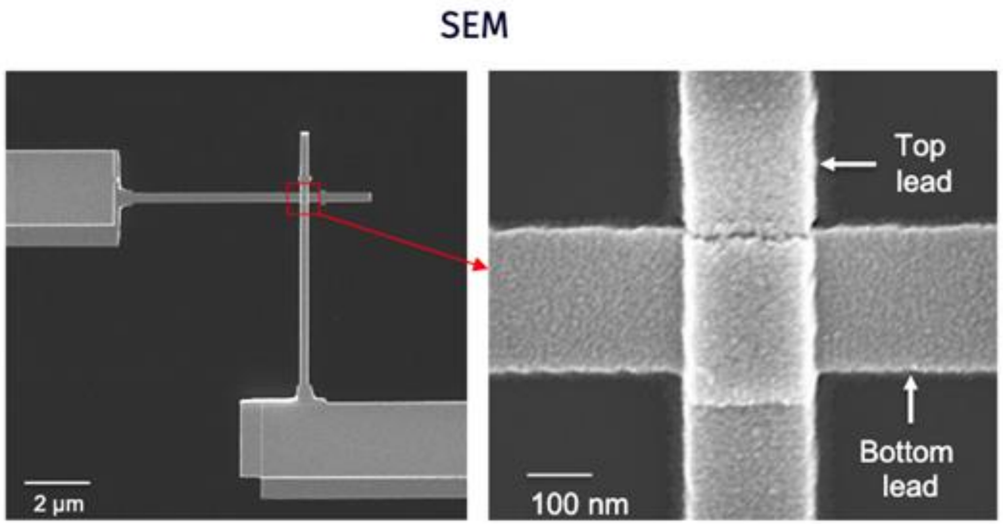
Use mask design to align data with physical dimensions and orientation…

★

Hafnium Junctions

LBL based team have successfully demonstrated **Hafnium Josephson Junctions** in a recent arXiv paper: https://arxiv.org/pdf/2510.25203





1. Double angled shadow evaporation technique
2. Hf deposited using e-beam evaporation
3. In-situ oxidation of HfOx tunnel barrier

TABLE I. Parameters of the measured Hf JJ.

Parameter	Symbol	Value
Critical current	I_c	6.2 nA
Superconducting gap	Δ	17.2 μeV
Normal-state resistance	R_N	5.2 kΩ
Critical temperature	T_c	0.125 K
Operating temperature	T_{op}	0.013 K
Josephson energy	E_J/h	3 GHz
Dynes parameter	γ (λ)	7.2 μeV
Junction area	A_{JJ}	0.16 μm^2

Summary

- Next generation science cases require finer energy resolving sensors
- Superconductors continue to offer a good avenue for progress
- Quantum sensors are starting to mature and become feasible for real use cases

SONIQ

SENSING OF NEUTRINOS IN QUBITS

Evading Noise

Noise & Backgrounds

The bane of every experimentalist's existence. When it comes to superconducting sensors, a bunch of things matter (non-exhaustive list):

- Thermal noise in any normal-metal parts or thermal fluctuations for a bolometer
- Intrinsic generation-recombination noise from Cooper-pair breaking and recombination
- Shot noise from discrete nature of charge carriers
- Cross-talk / electrical RF
- Two level systems (TLS)
- Weird background excesses (LEE)
- Amplifier noise from readout chain

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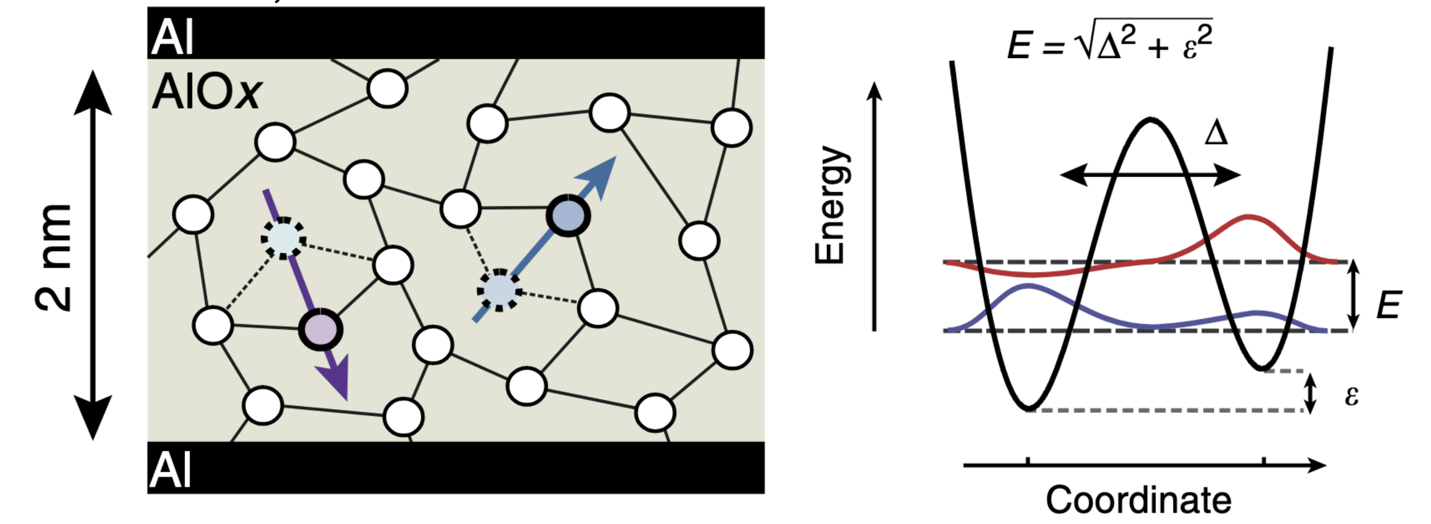
Two Level Systems

Dissipation caused by electrically active two level (or n-level) systems present in surface oxides or other layers.

→ Electric dipole moment, responds to external EM wave, causes fluctuations in resonant superconducting structures.

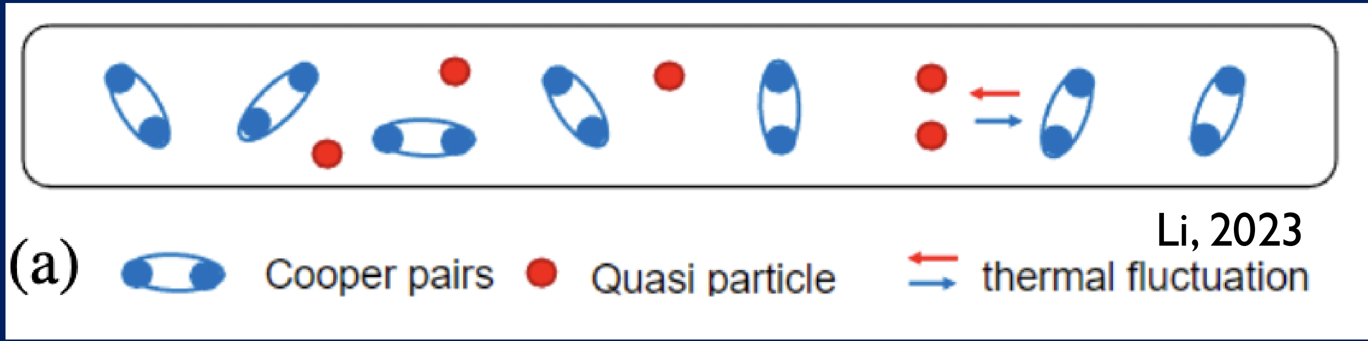
→ **Manifests as a ~1/f noise**

Lisenfield 2015, Wen 2024



Noise & Backgrounds

Generation-Recombination



Li, 2023

... it comes to ... non-exhaustive list):

... mal fluctuations for a bolometer

- Intrinsic generation-recombination noise from Cooper-pair breaking and recombination
- Sho...
- Cross-talk / electrical RF
- Two level systems (TLS)
- Amplifier noise from

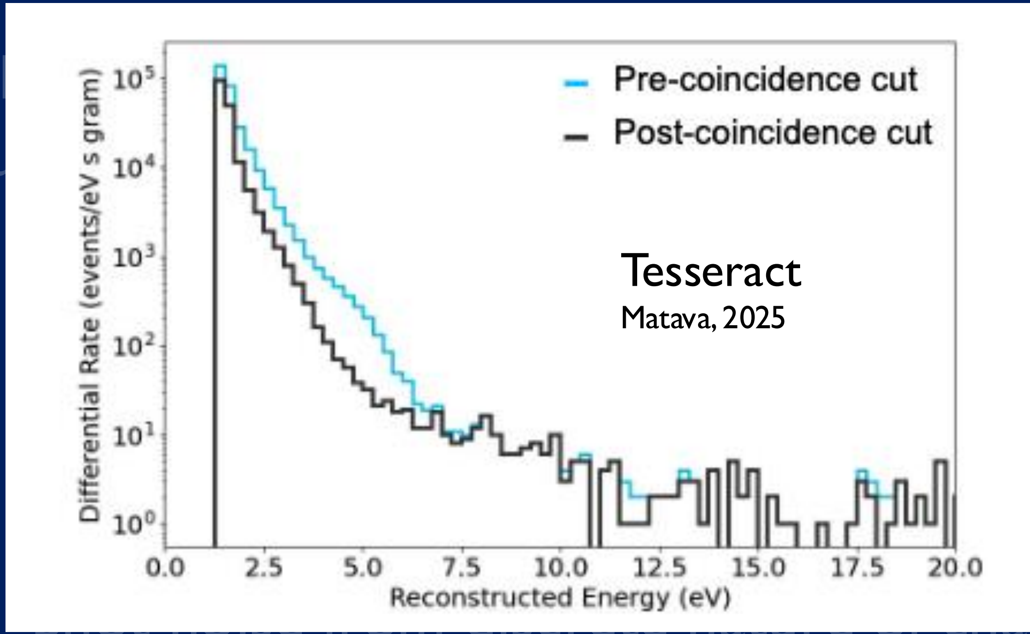
Stochastic fluctuations in quasiparticle density

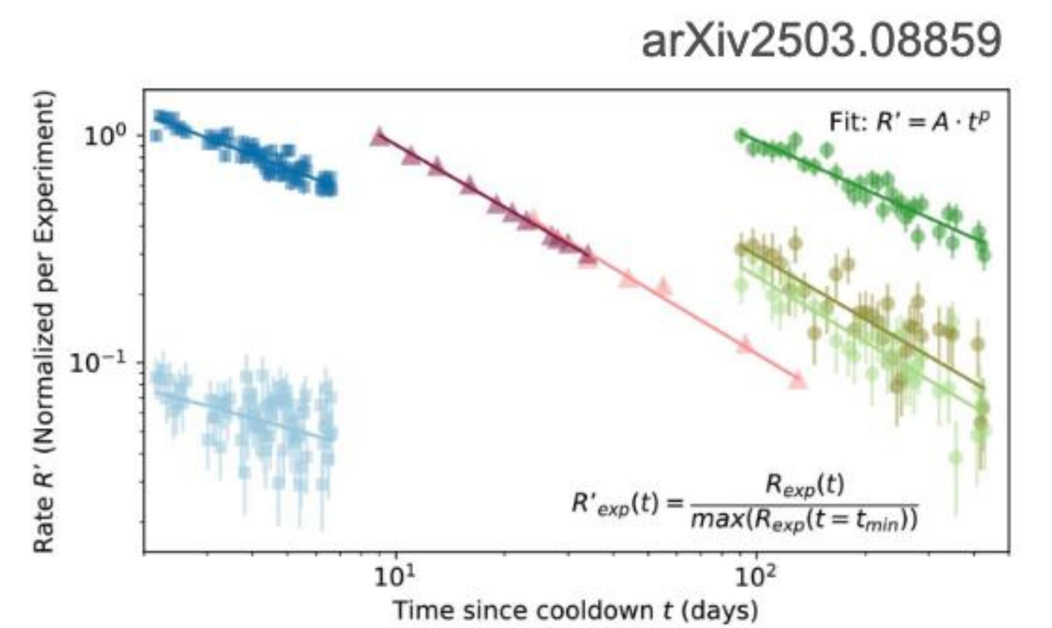
→ Can be from **thermal** or **parasitic** (e.g. external radiation) pair-breaking processes

→ Limits quasiparticle lifetimes; manifests as a white spectrum with roll-off at lifetime.

Noise & Backgrounds

*Low Energy Excess





- Cross-talk / electrical RF
- Two level systems (TLS)
- Amplifier noise from

Regardless of detector modality, vintage, what it's sensitive too – always see a large increase in event rate closer to threshold. Semi-unknown origin: stress in substrate? film?

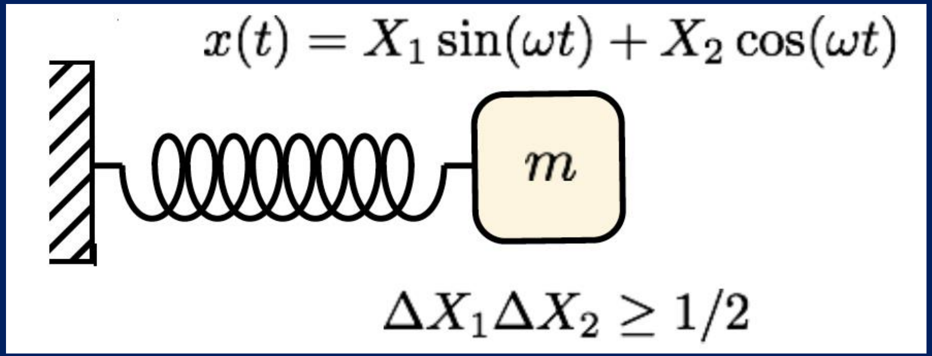
But can’t a dogged scientist just reduce parasitic backgrounds and fabricate higher quality detectors and just keep beating down noise?

Not totally.

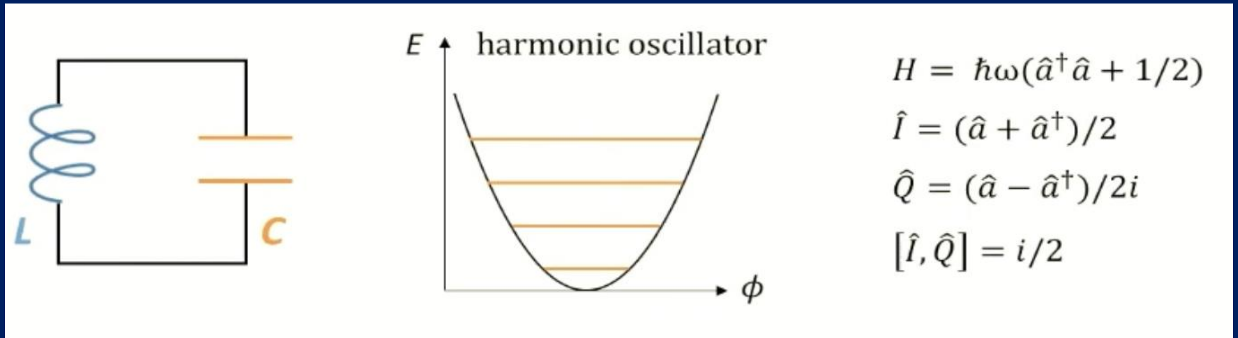
The Standard Quantum Limit

Standard Quantum Limit - Vacuum

Quantum systems have intrinsic fluctuations



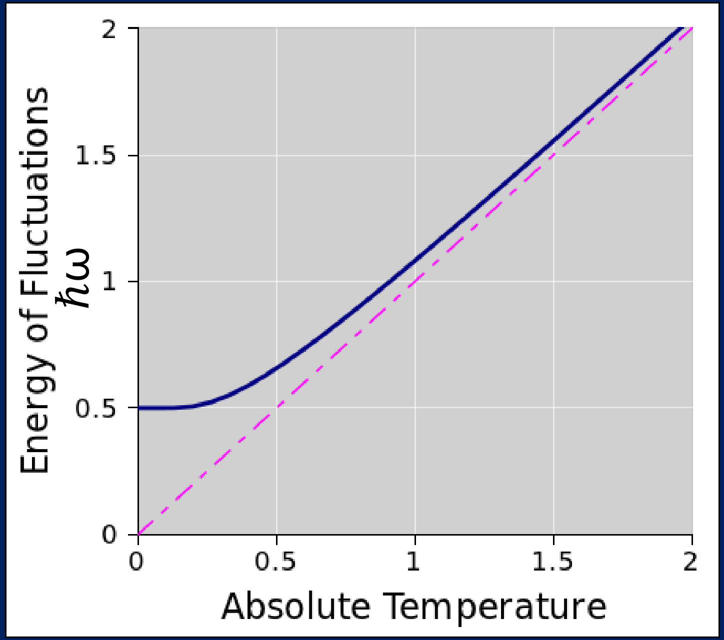
Vacuum fluctuations dictate a minimum noise level



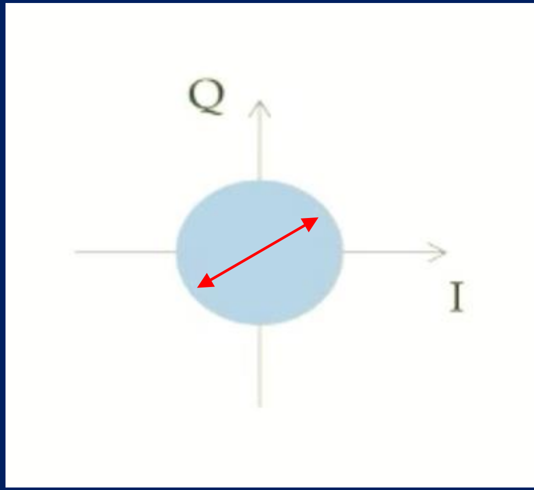
Number of thermal noise photons in an oscillator at temperature T

$$n_{\mathrm{eq}} = \langle I^2 \rangle + \langle Q^2 \rangle = \coth \frac{\hbar\omega_0}{2kT}$$

Fluctuations are "**1/2** photon per mode"

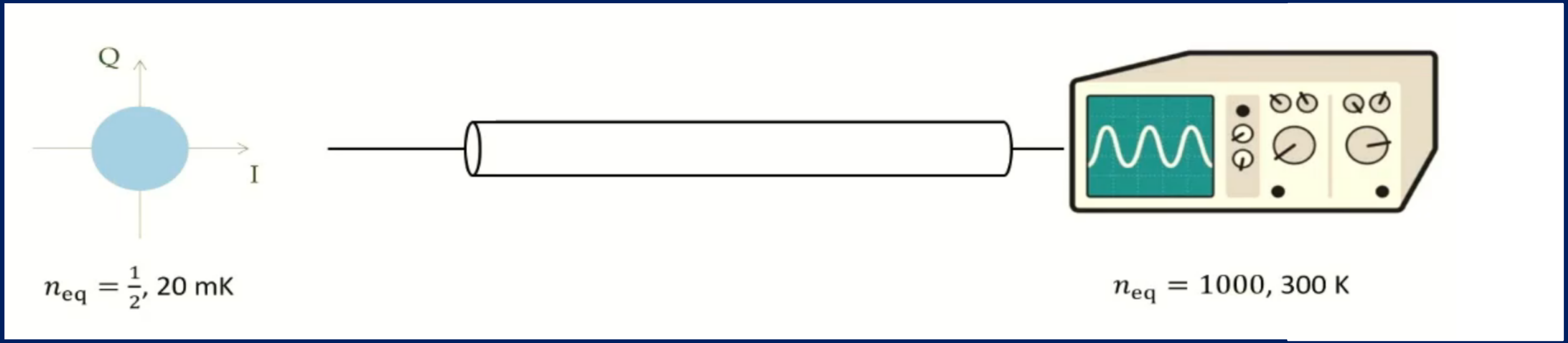


Make measurements of orthogonal quadratures, fundamental lower bound

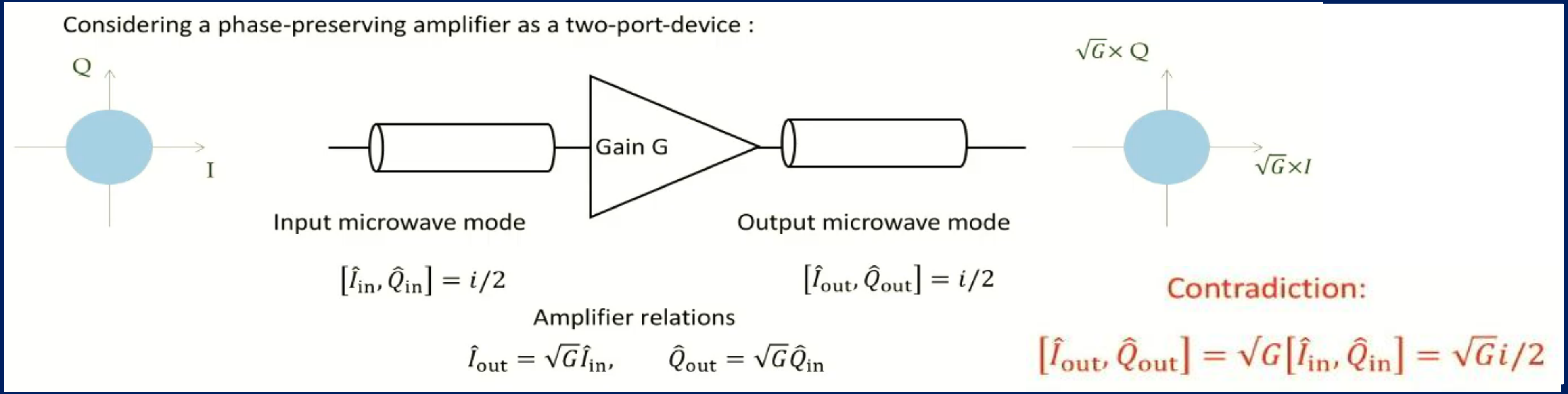


A. Bienfait, 2019

Standard Quantum Limit - Amplification

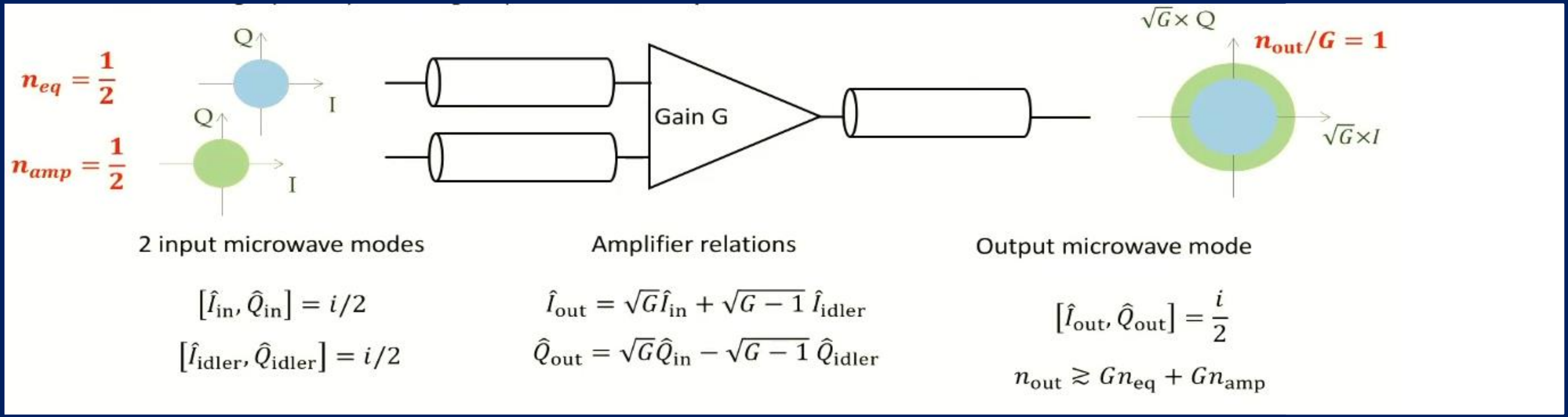


Amplification of some generic state



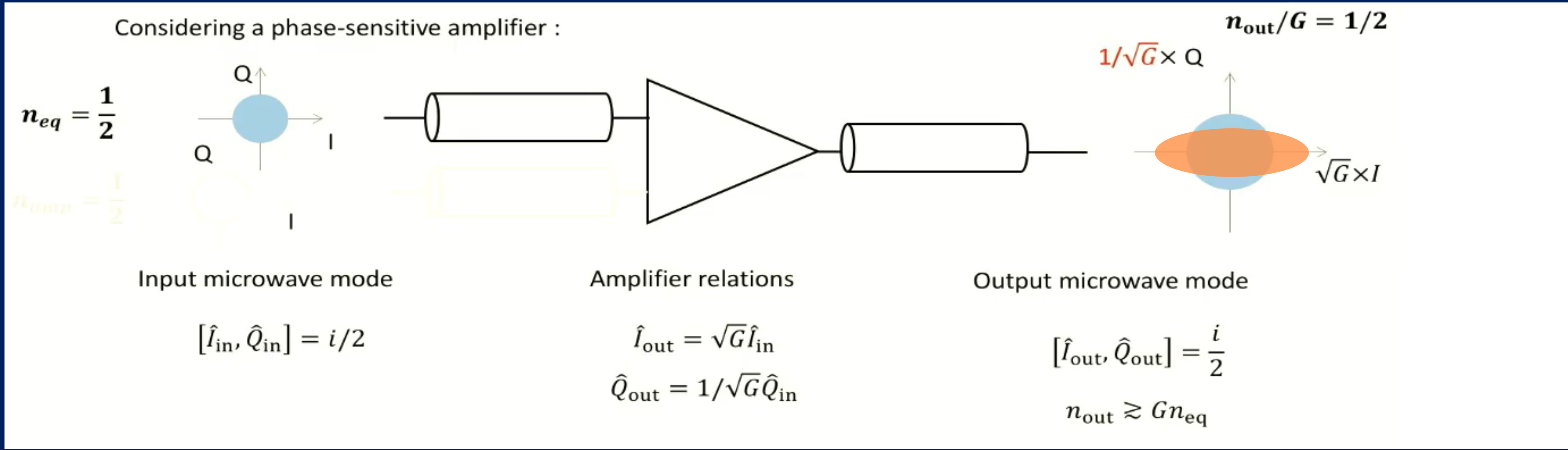
Let's introduce a "phase preserving amplifier" with gain G & enforce commutation relations on operators

Standard Quantum Limit - Amplification



What's actually happening? Amplifier adds noise via "idler" channel.

Note this is **phase preserving** (i.e. **phase insensitive**)



Can do **phase sensitive** amplification of one quadrature only

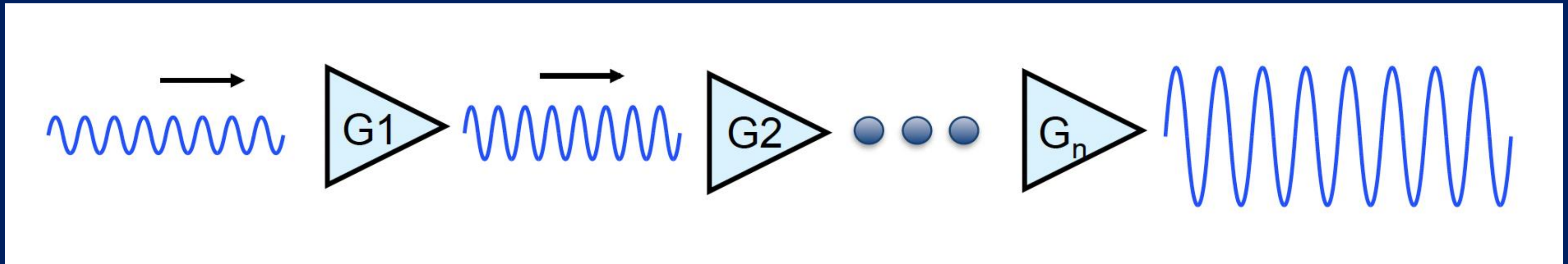
Shunt the noise into the other quadrature

--> **Squeezing**

A. Bienfait, 2019

Why does this matter?

Multi-stage amplification:



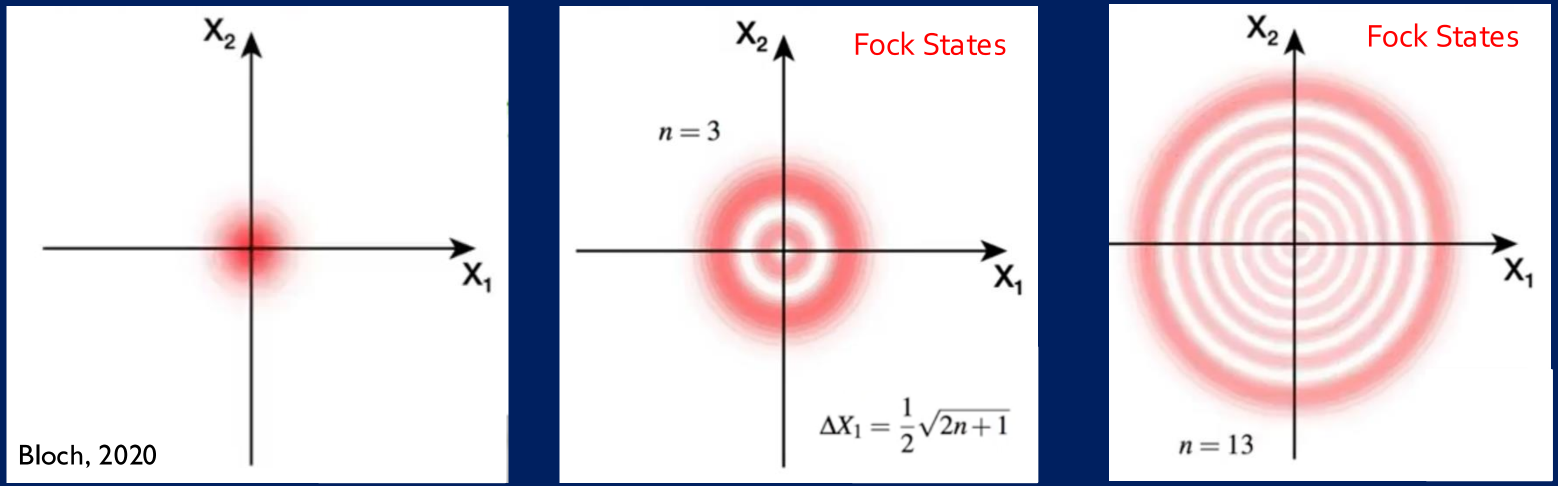
Noise propagates as:

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \ldots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}$$

Noise often set by the very first loss/amplification element after your detector!

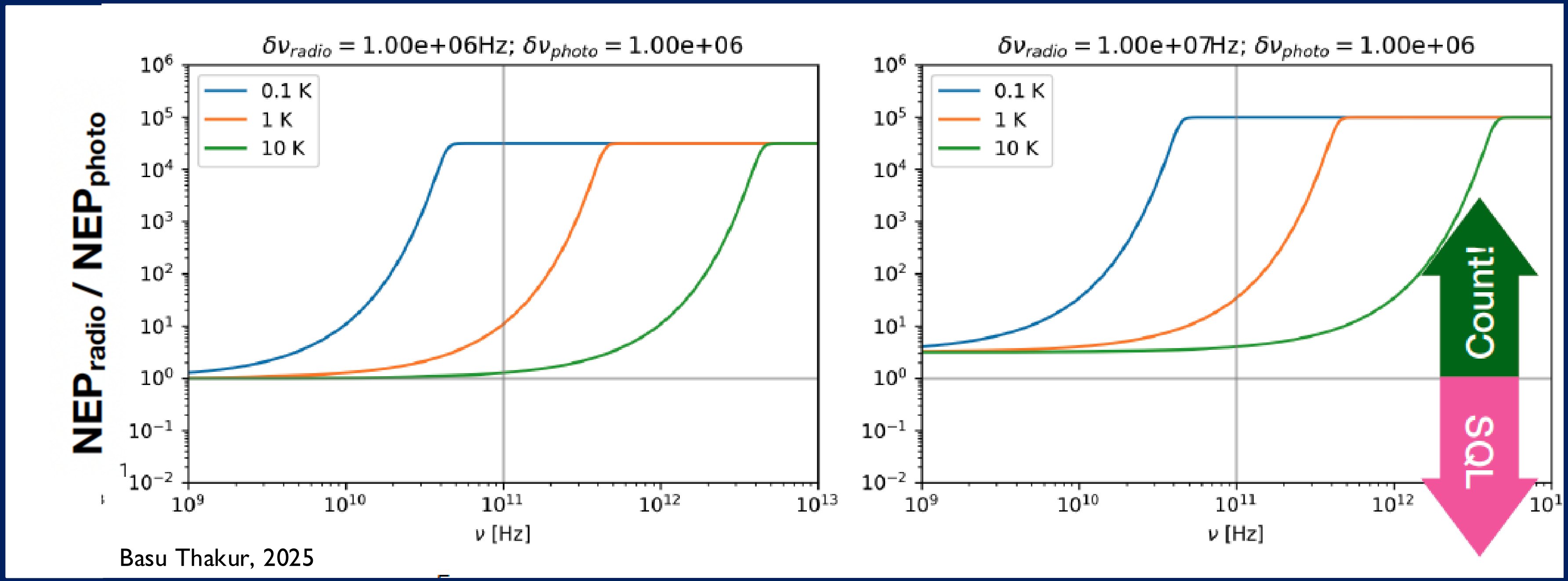
Qiu, 2017

Can count photons instead

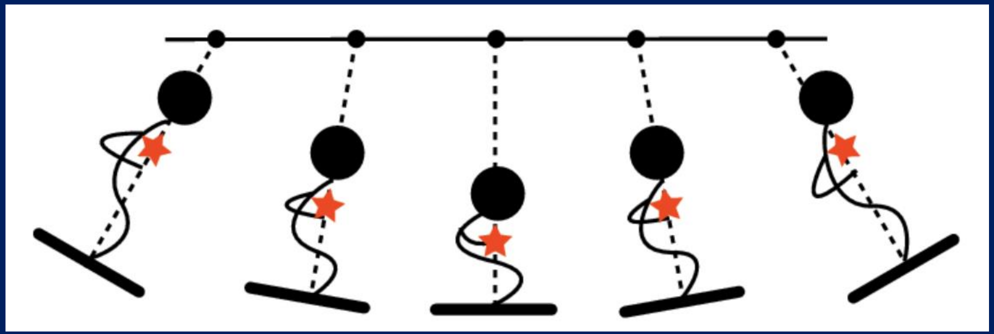


By changing measurement system one can also count photons, which allows you to circumvent the prior limits – but lose all phase information (you might not care)

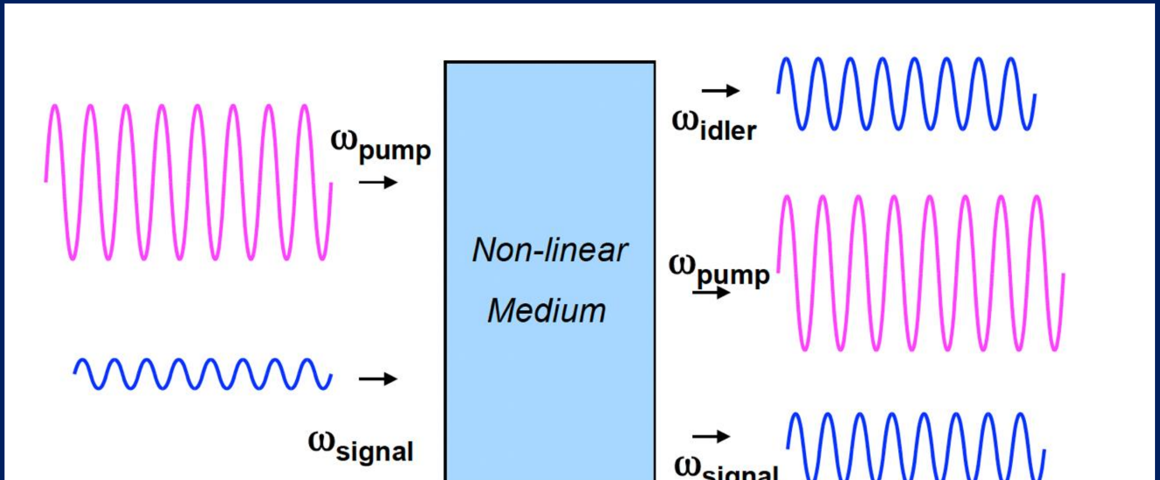
Depending on temperature, energy, measurement bandwidth etc. one scheme can better than the other



Parametric Amplification



Consider a child on a swing. By dynamically changing a parameter (the CoM location), pump energy into system and increase swing height.



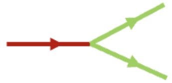
Qiu, 2017

Introduce a non-linear medium and provide external energy in the form of a ”pump” tone. Energy transfers to signal tone. No free lunch, also get out the idler tone

3-Wave Mixing

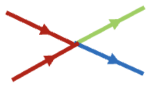
1) Non-degenerate: ω_p != ω_s != ω_i ; $\omega_p = \omega_s + \omega_i$

2) Degenerate: $\omega_p = 2\omega_s$

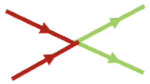


4-Wave Mixing

1) Non-Degenerate: $2\omega_p = \omega_s + \omega_i$

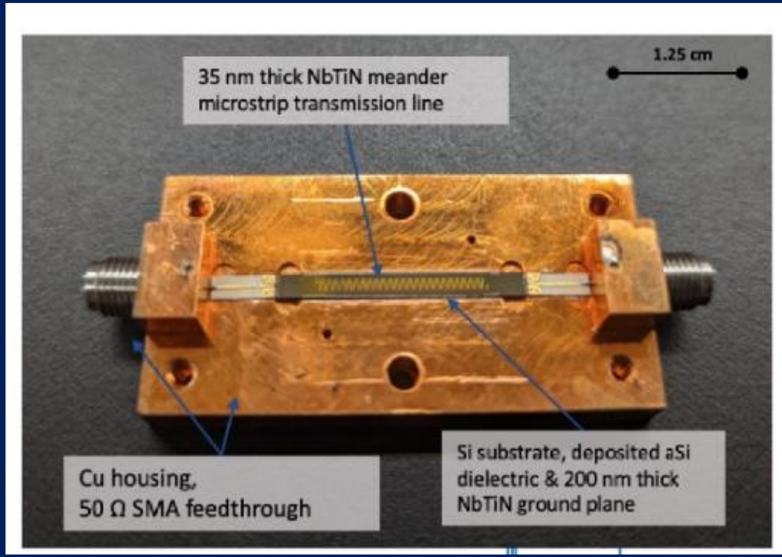


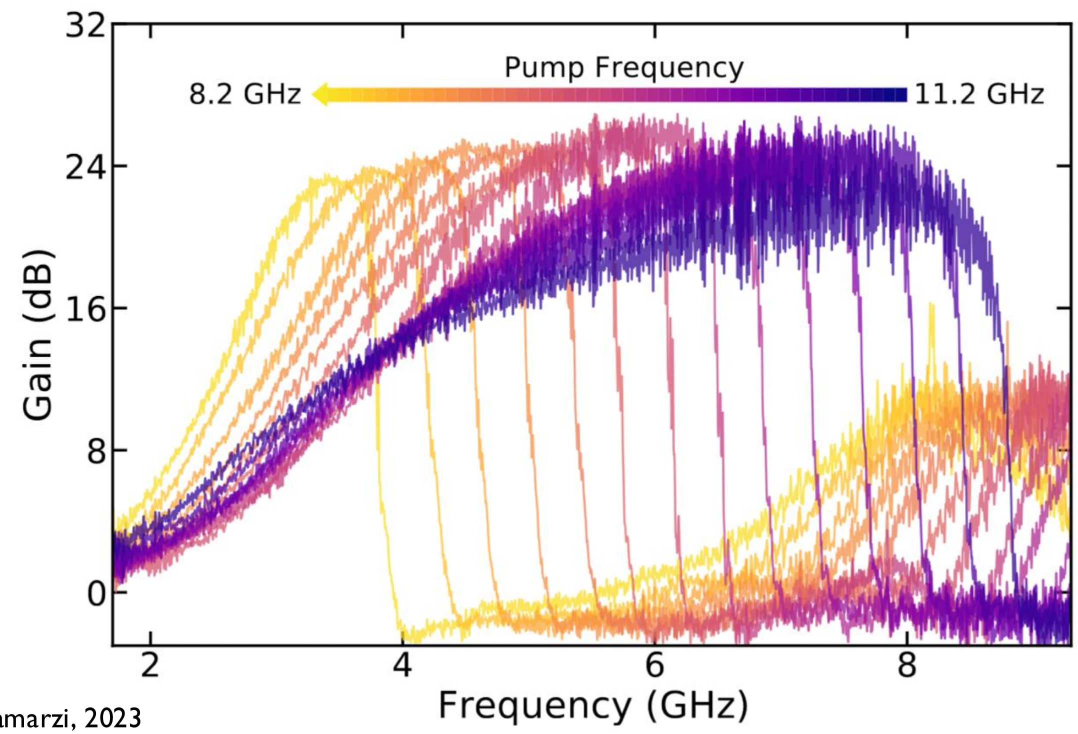
2) Doubly Degenerate: $\omega_p = \omega_s$ (= ω_i)



Different operation modes – depending on number of input and output tones. Degenerate modes allows you to do phase sensitive squeezing

Kinetic Inductance Parametric Amplifiers

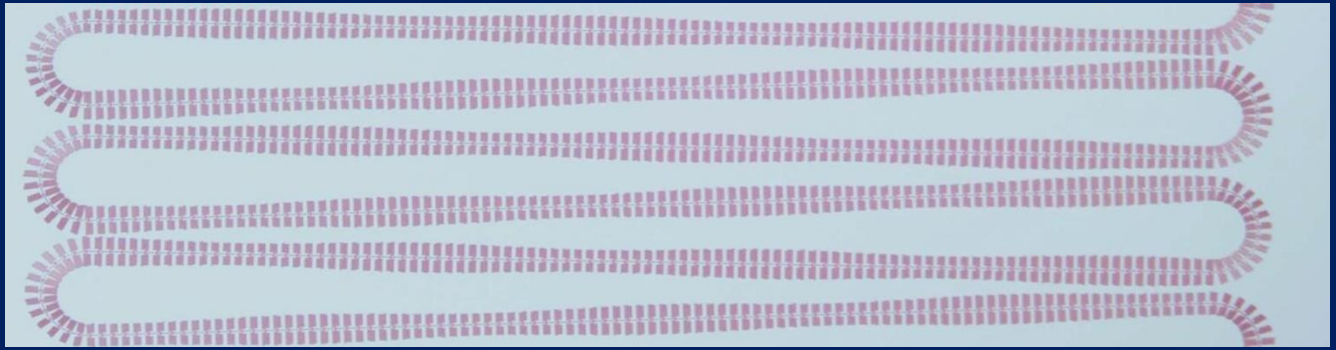




Faramarzi, 2023

$$L_K(I) = L_K(0)\left(1 + \frac{I^2}{I_*^2} + \ \ldots\right)$$

Exploits kinetic inductance non-linearity. The I^2 term mixes pump and signal



THANKS! QUESTIONS?

karthikr@wustl.edu

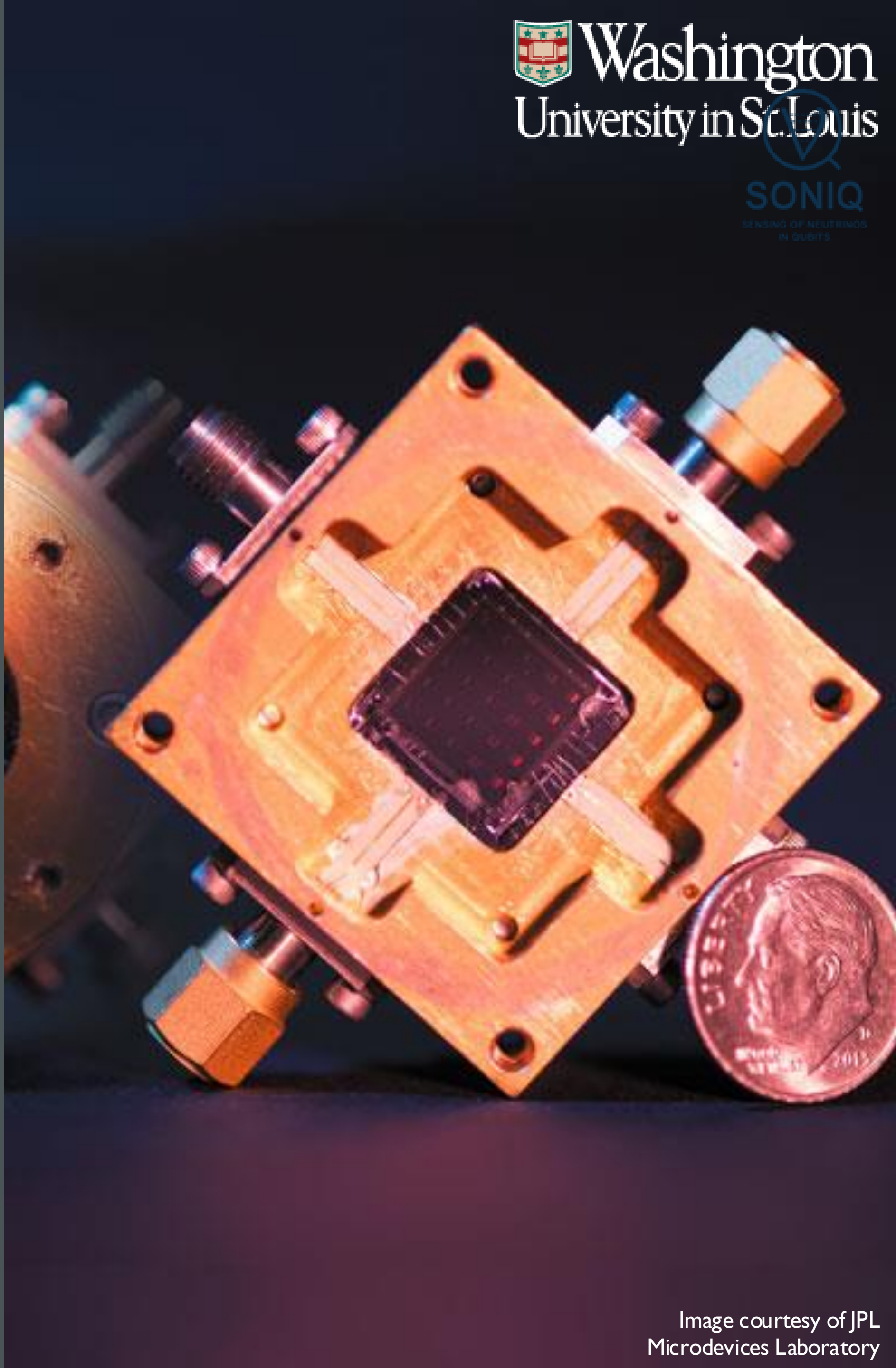


Image courtesy of JPL Microdevices Laboratory